The Planetary Science of Exoplanets

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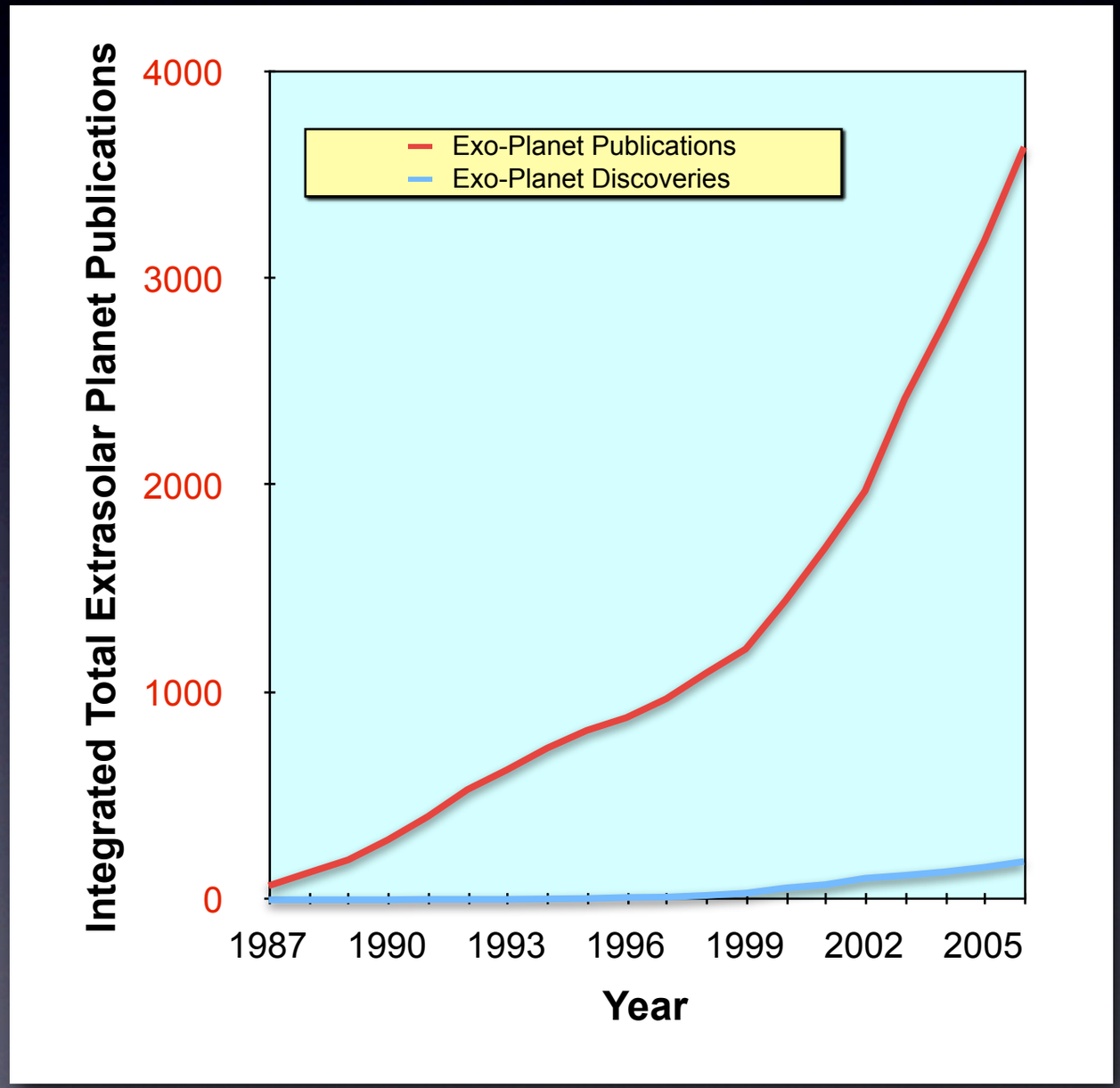
Richard Freedman

Age of Exoplanet Characterization

- 270 exoplanets
- About two dozen transiting planets
- Spitzer, HST, MOST, COROT, Kepler, JWST...



Solar System Heritage

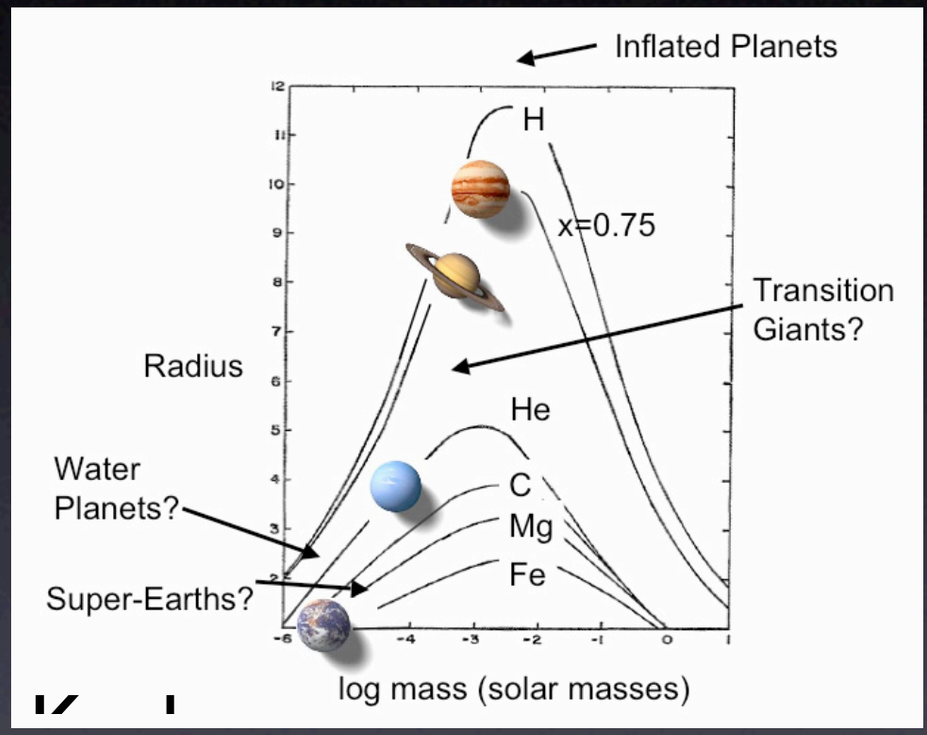
- Decades of in situ planetary exploration
- Appreciation for key processes
  - Stratospheres
  - Clouds
  - Atmospheric dynamics
  - Interior structures....
- Many opportunities for leveraging investment

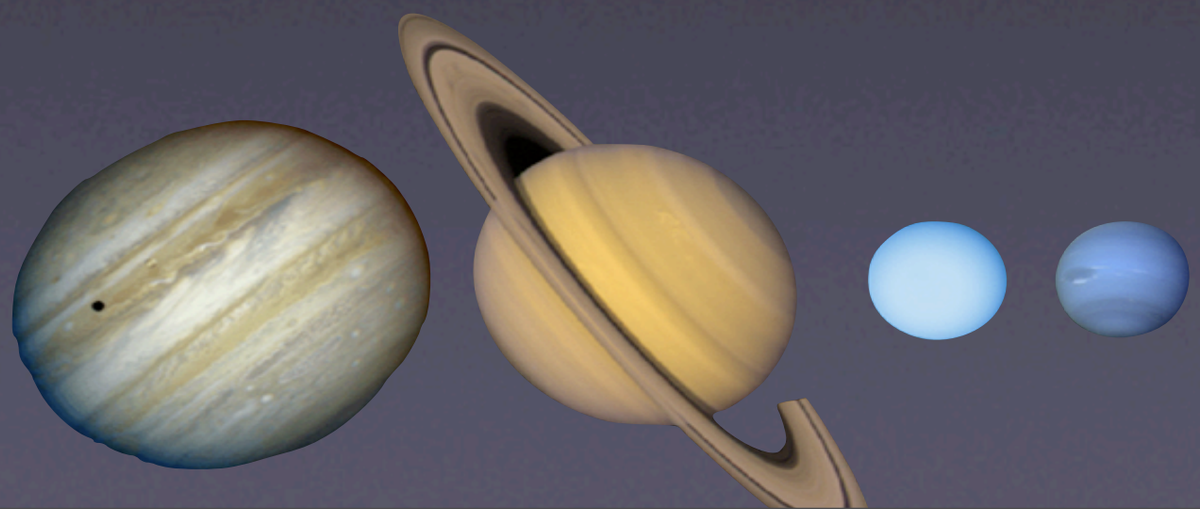
Today

- Why characterize extrasolar giant planets?
- Stratospheres
  - two classes of hot Jupiters
  - heritage: photochemistry
- Clouds
  - clouds in exoplanets
  - heritage: solar system & brown dwarfs

Goals of Characterization

- Mass and Radius
- Composition
- Atmospheric structure
- Atmospheric dynamics





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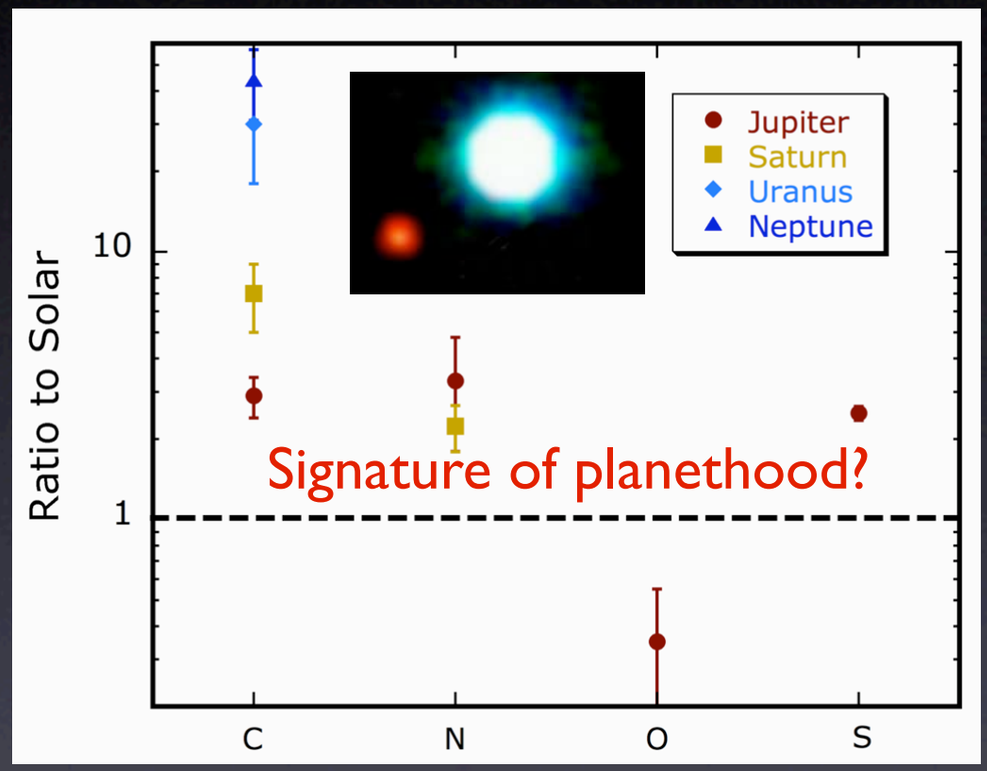

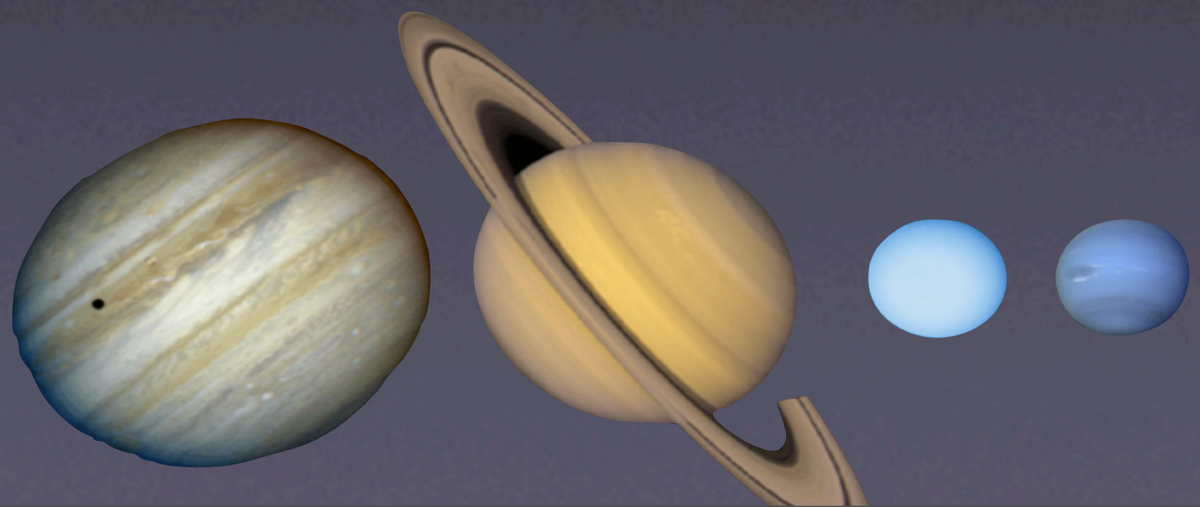

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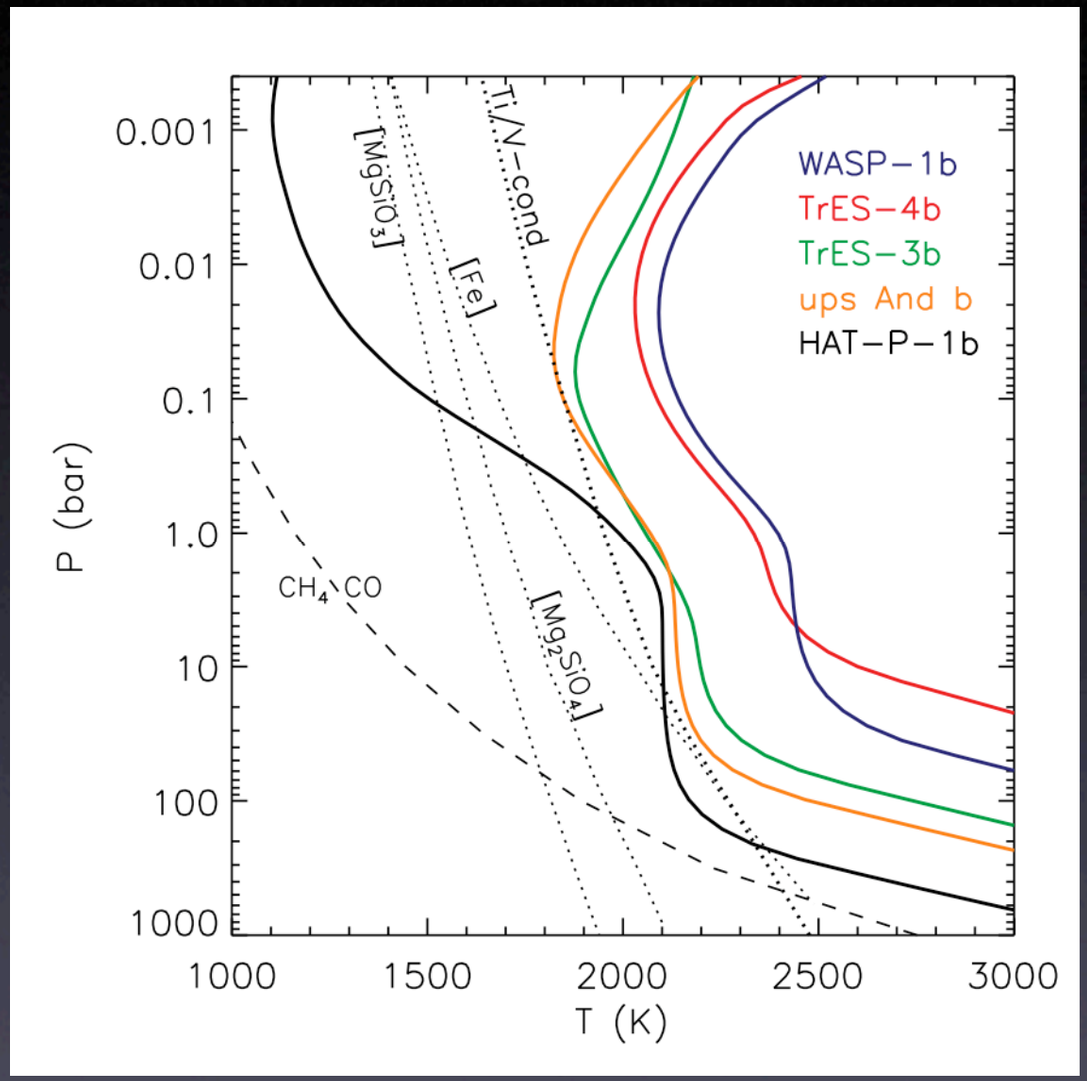

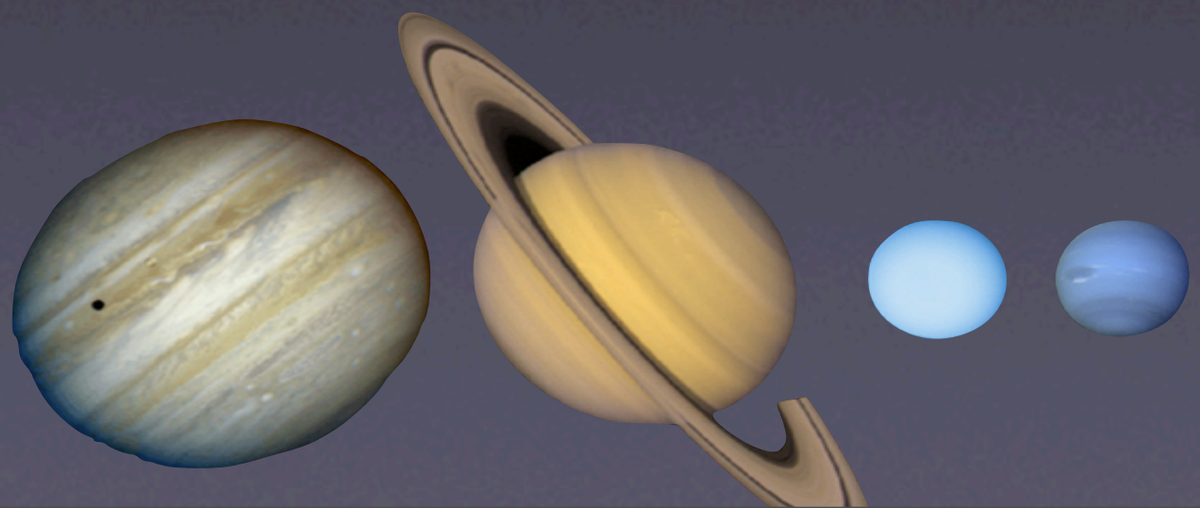

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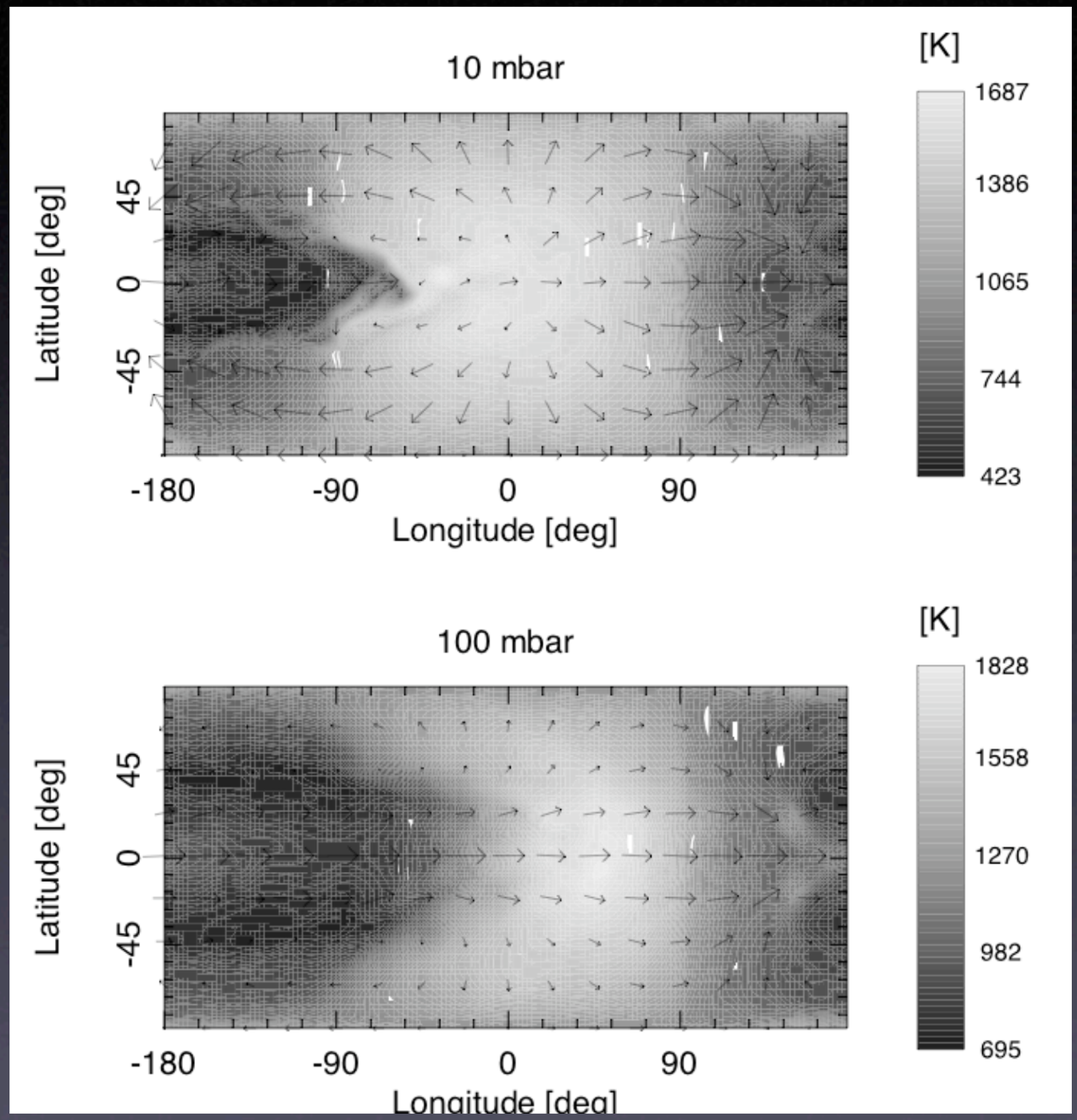

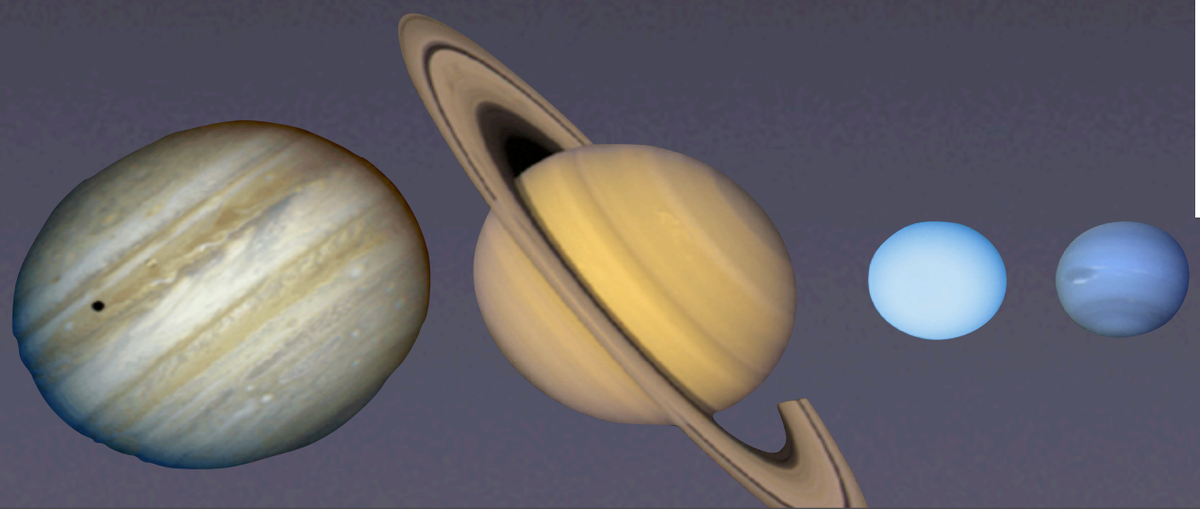

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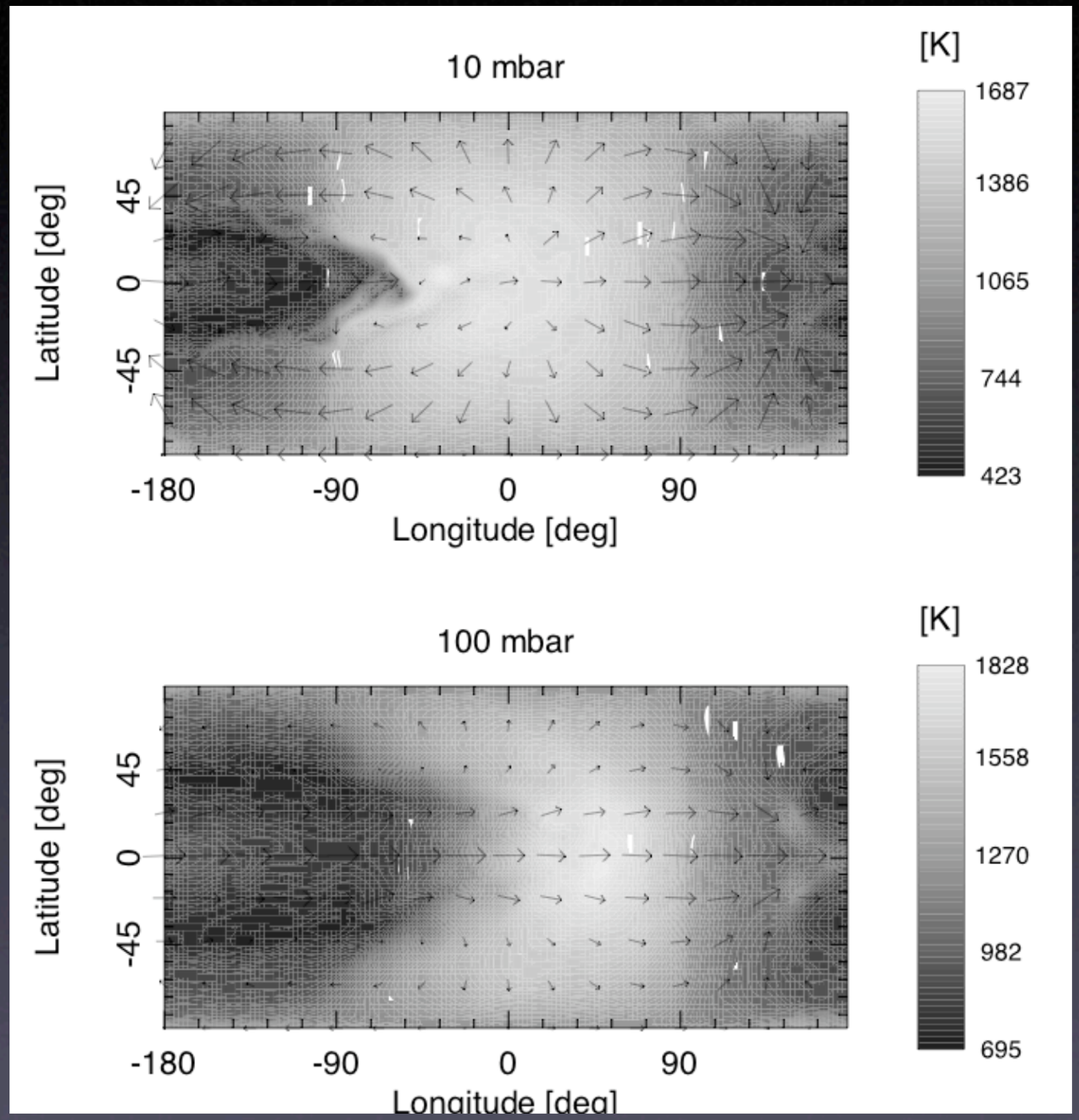

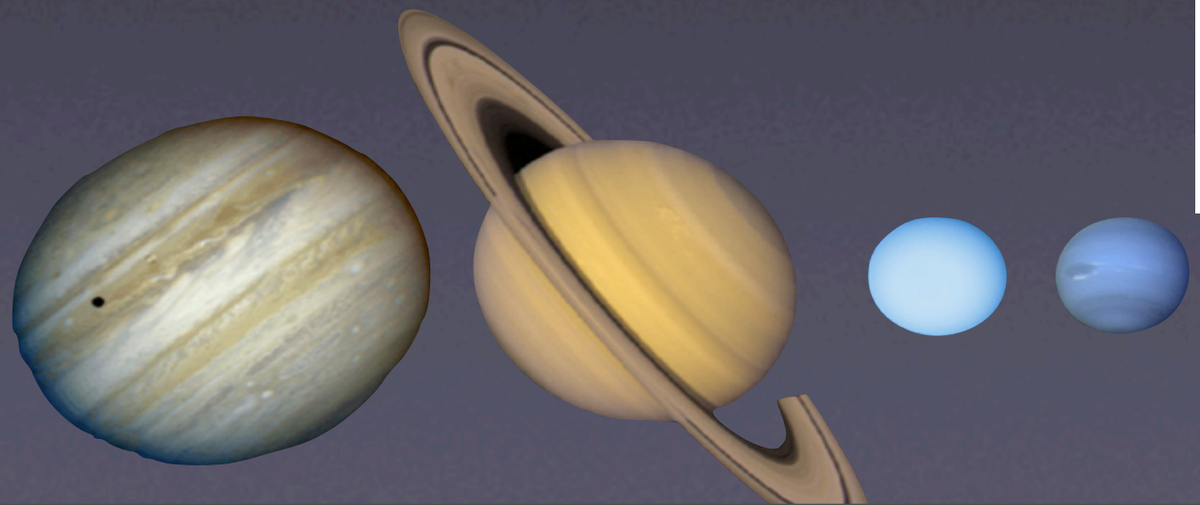

Why Characterize Giants?

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- Giants provide a record of stellar system formation & perhaps volatile transport
- Giant planet science provides end to end experience of planet characterization, heritage for bigger efforts
- Extend understanding of key solar system processes under extreme new domains

Need Models!

Composition

Chemistry

Opacities

Condensates

\+ Dynamics

Thermal Structure & Spectrum

Composition — Metallicity, C/O, ...

Chemistry

Opacities

Condensates

\+ Dynamics

Thermal Structure & Spectrum

Composition — Metallicity, C/O, ...

Chemistry — Sedimentation

Opacities

Condensates

\+ Dynamics

Thermal Structure & Spectrum

Composition	Metallicity, C/O, ...
Chemistry	Sedimentation
Opacities	High *T* CH_4

Condensates

\+ Dynamics

Thermal Structure & Spectrum

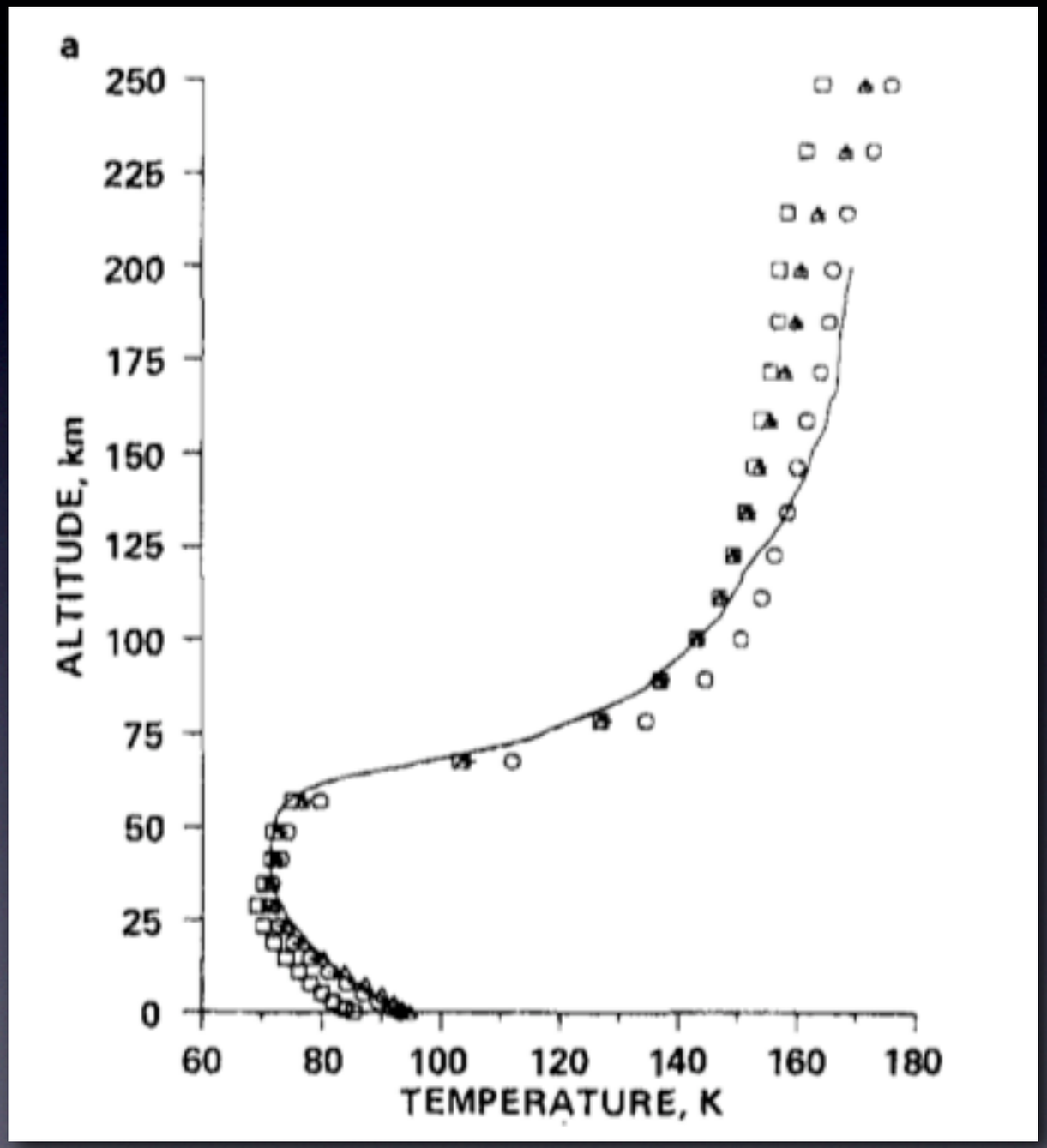
Composition	Metallicity, C/O, ...
Chemistry	Sedimentation
Opacities	High *T* CH_4
Condensates	Cloud Physics
+ Dynamics	

Thermal Structure & Spectrum

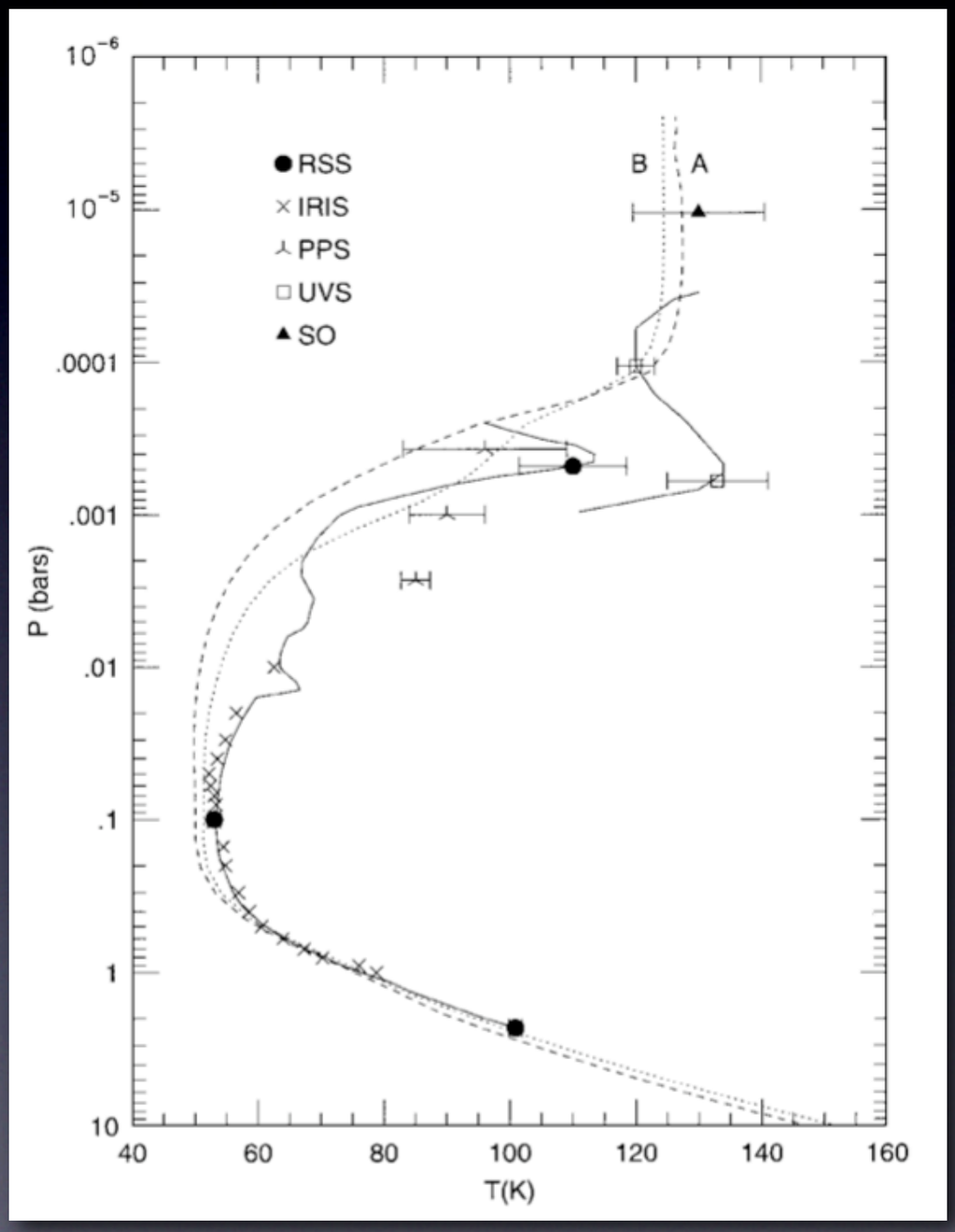
Composition	Metallicity, C/O, ...
Chemistry	Sedimentation
Opacities	High *T* CH_4
Condensates	Cloud Physics
+ Dynamics	Circulation, *f*

Thermal Structure & Spectrum

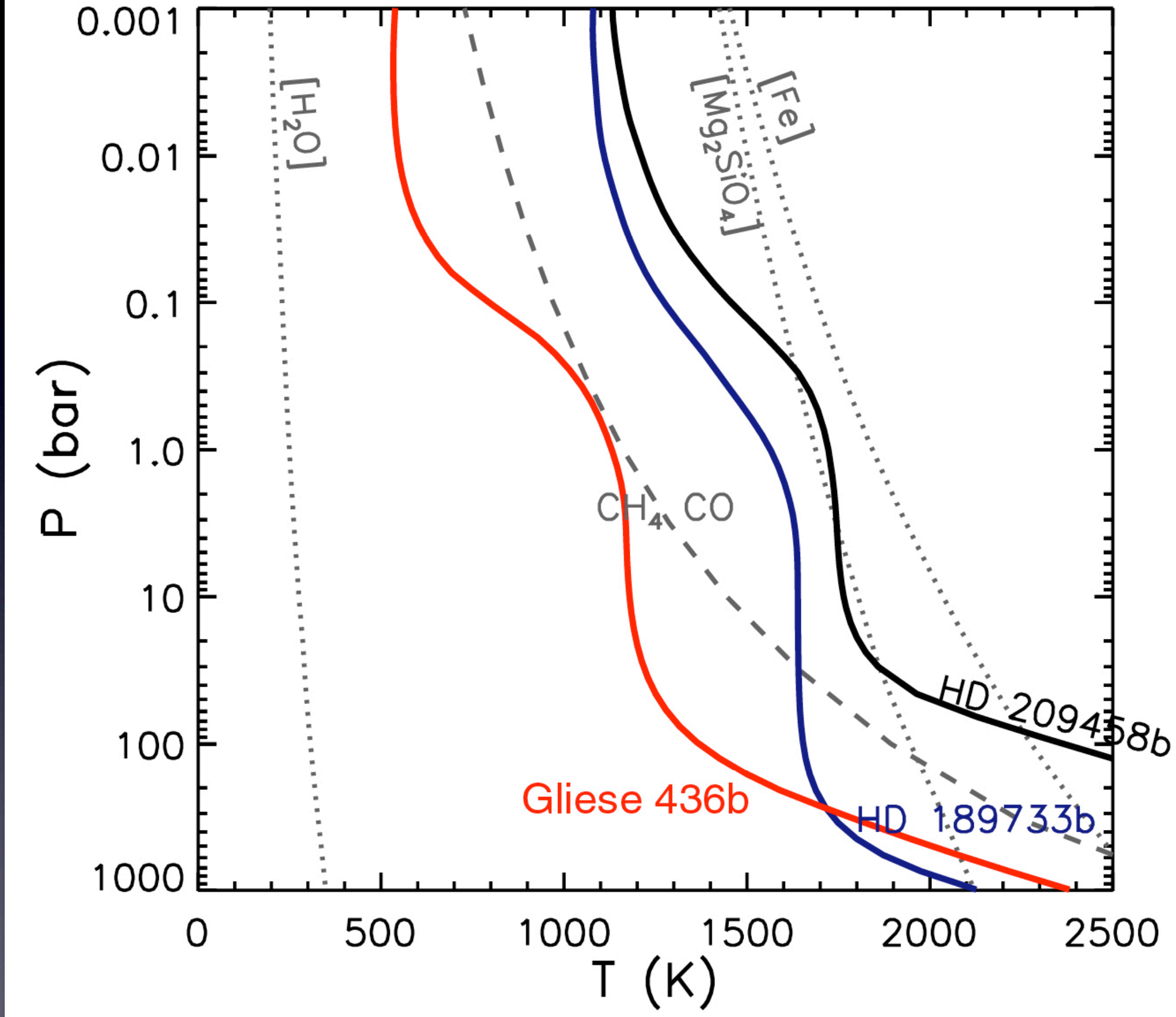
Solar System Heritage

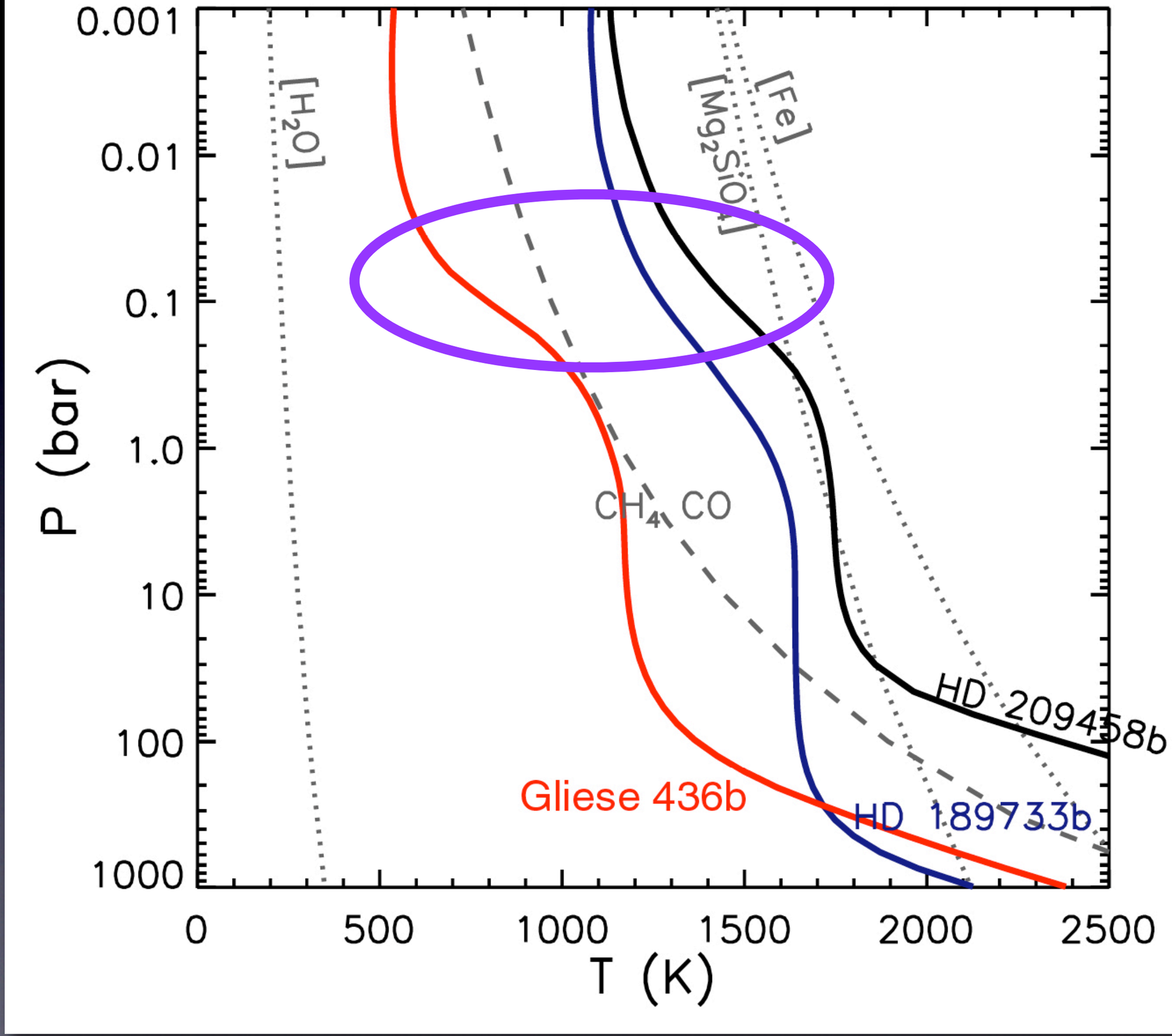


McKay, Pollack & Courtin (1989)



Marley & McKay (1999)


0.001
0.01
0.1
1.0
10
100
1000
P (bar)
0
500
1000
1500
2000
2500
T (K)
[H2O]
[Fe]
[Mg2SiO4]
CH4, CO
Gliese 436b
HD 189733b
HD 209458b


0.001
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P (bar)
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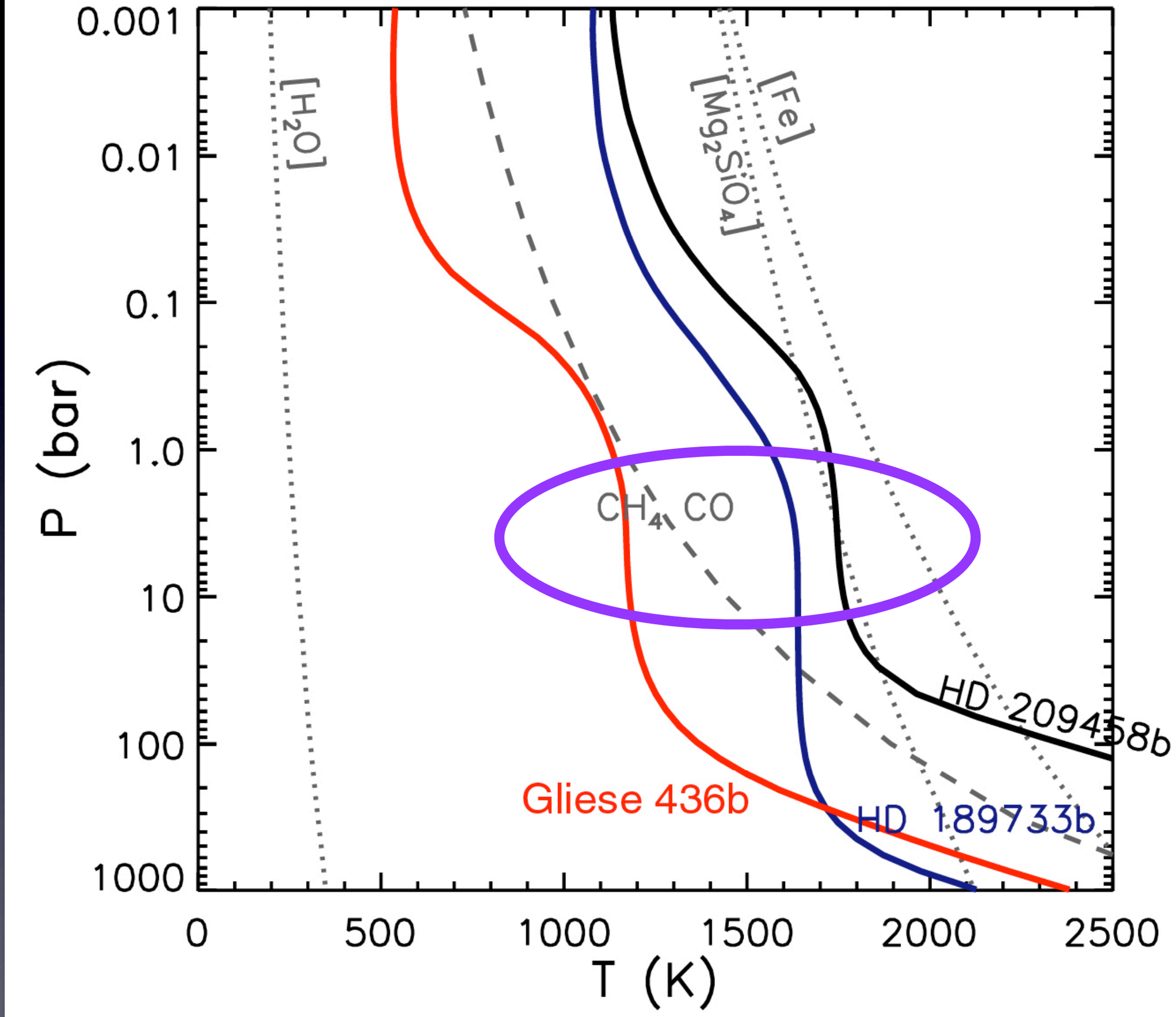
0.001
0.01
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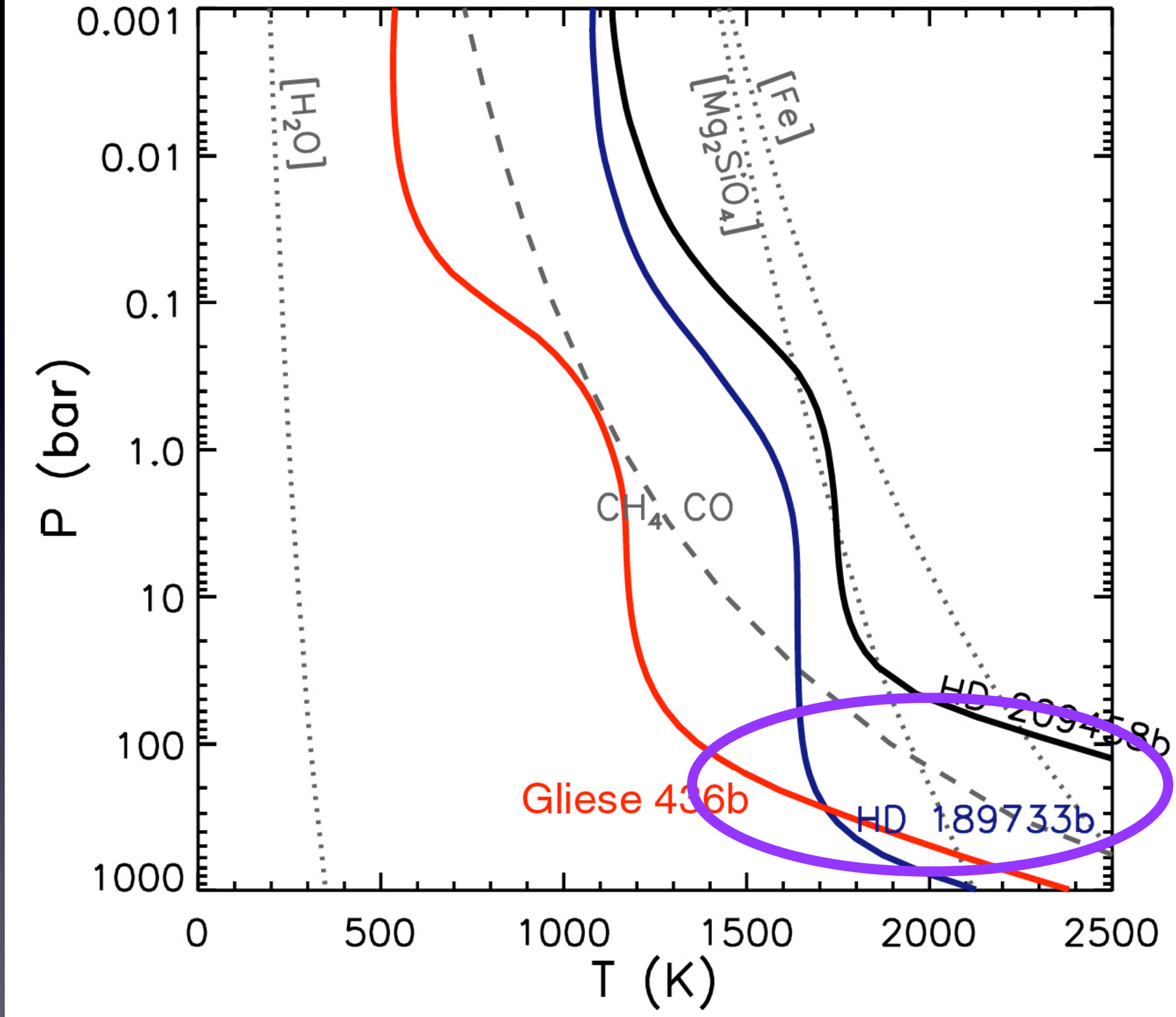
0.001
0.01
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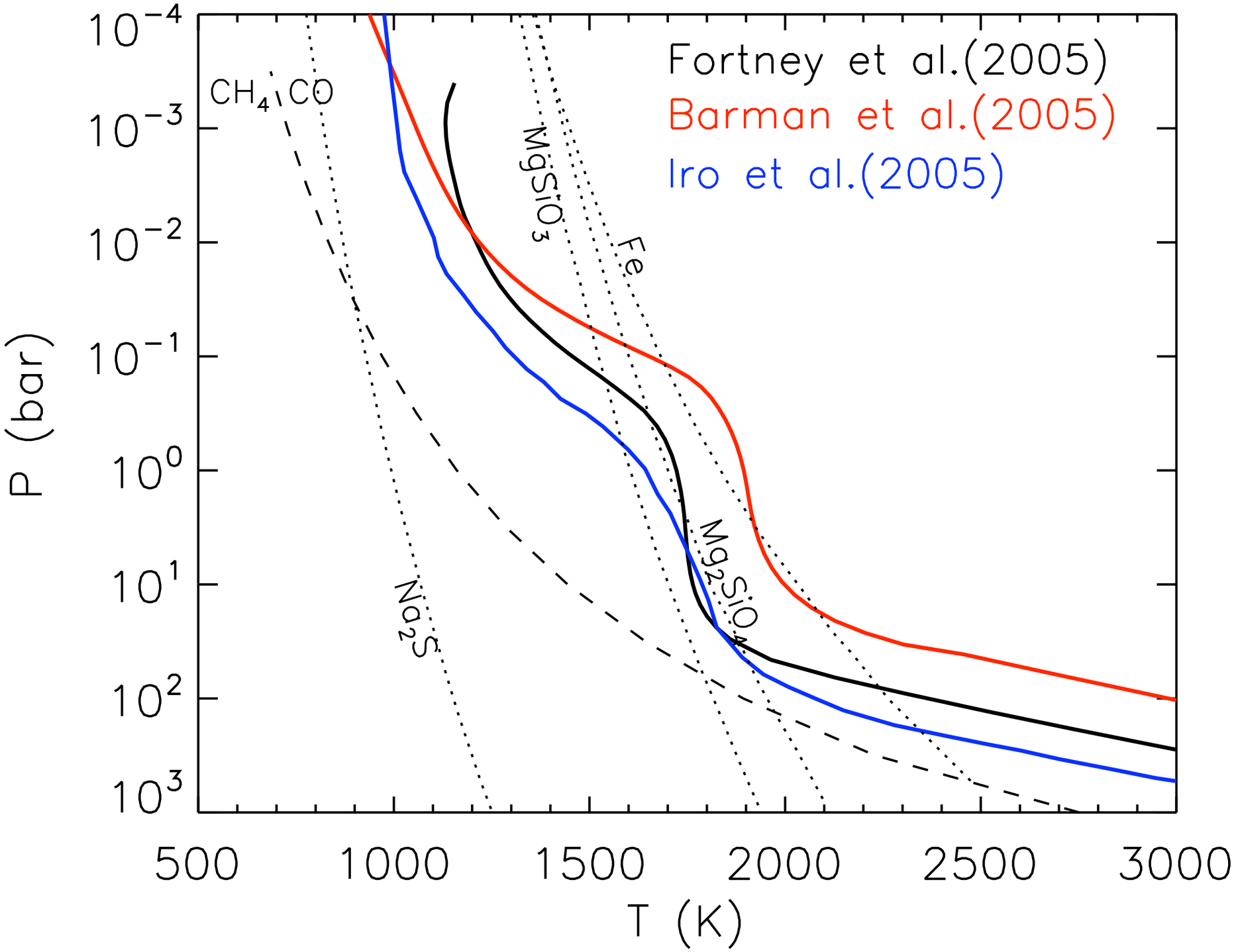
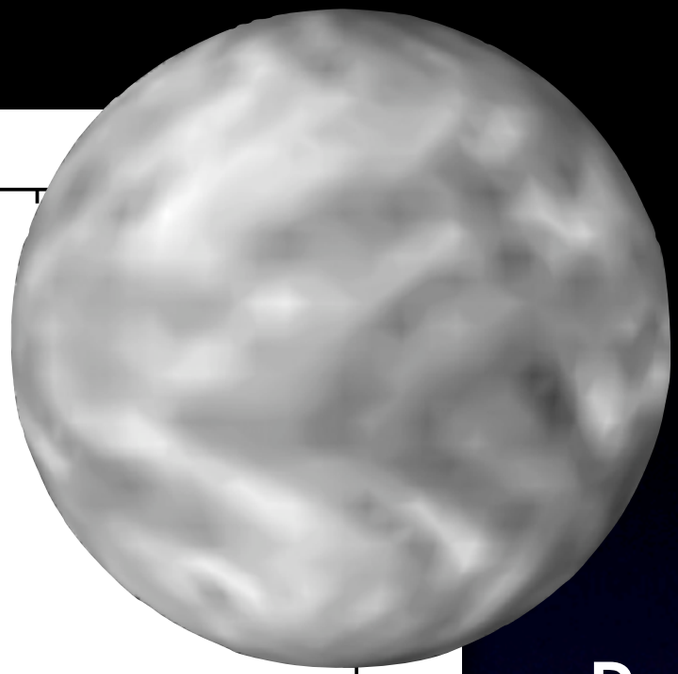
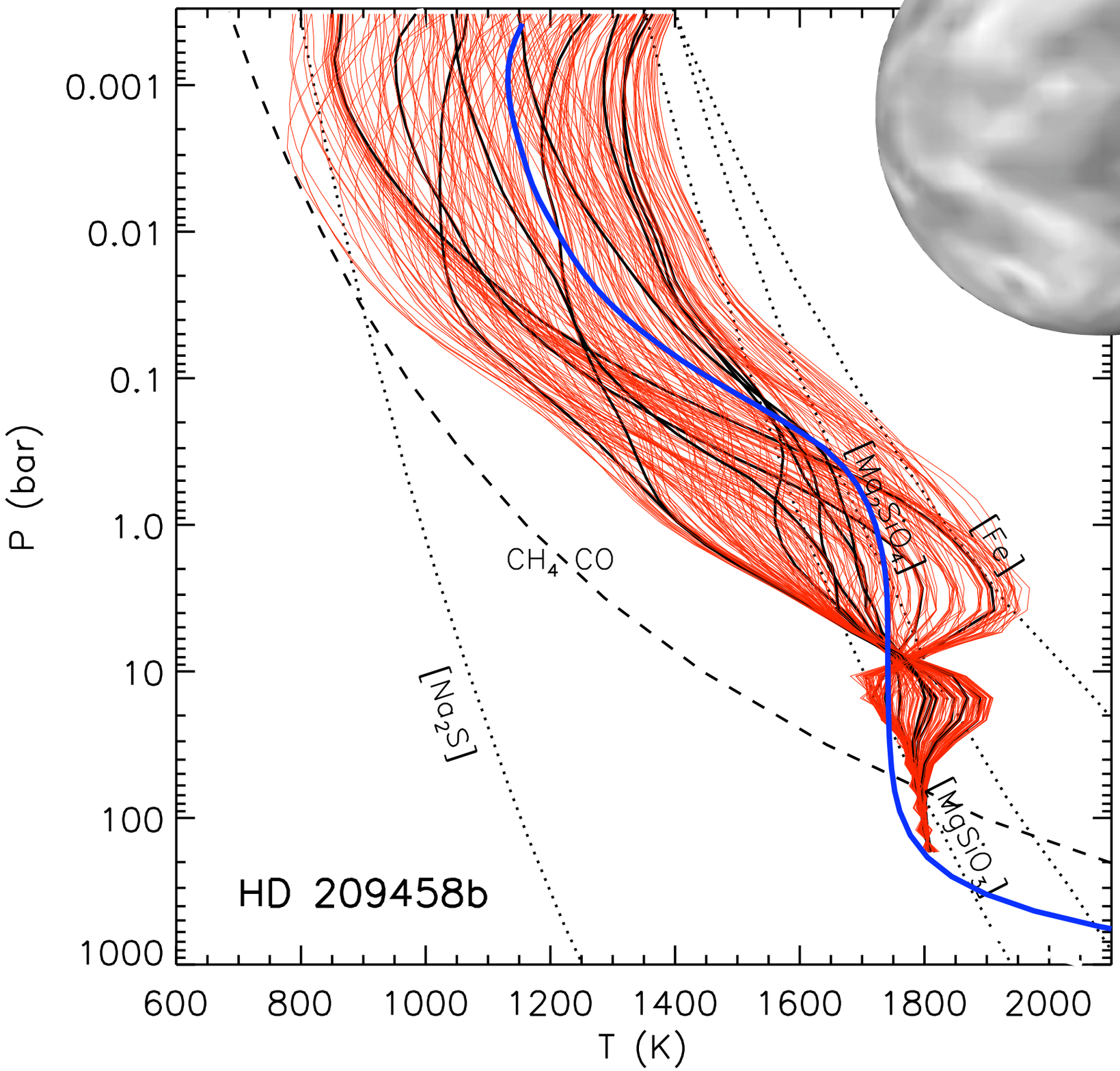
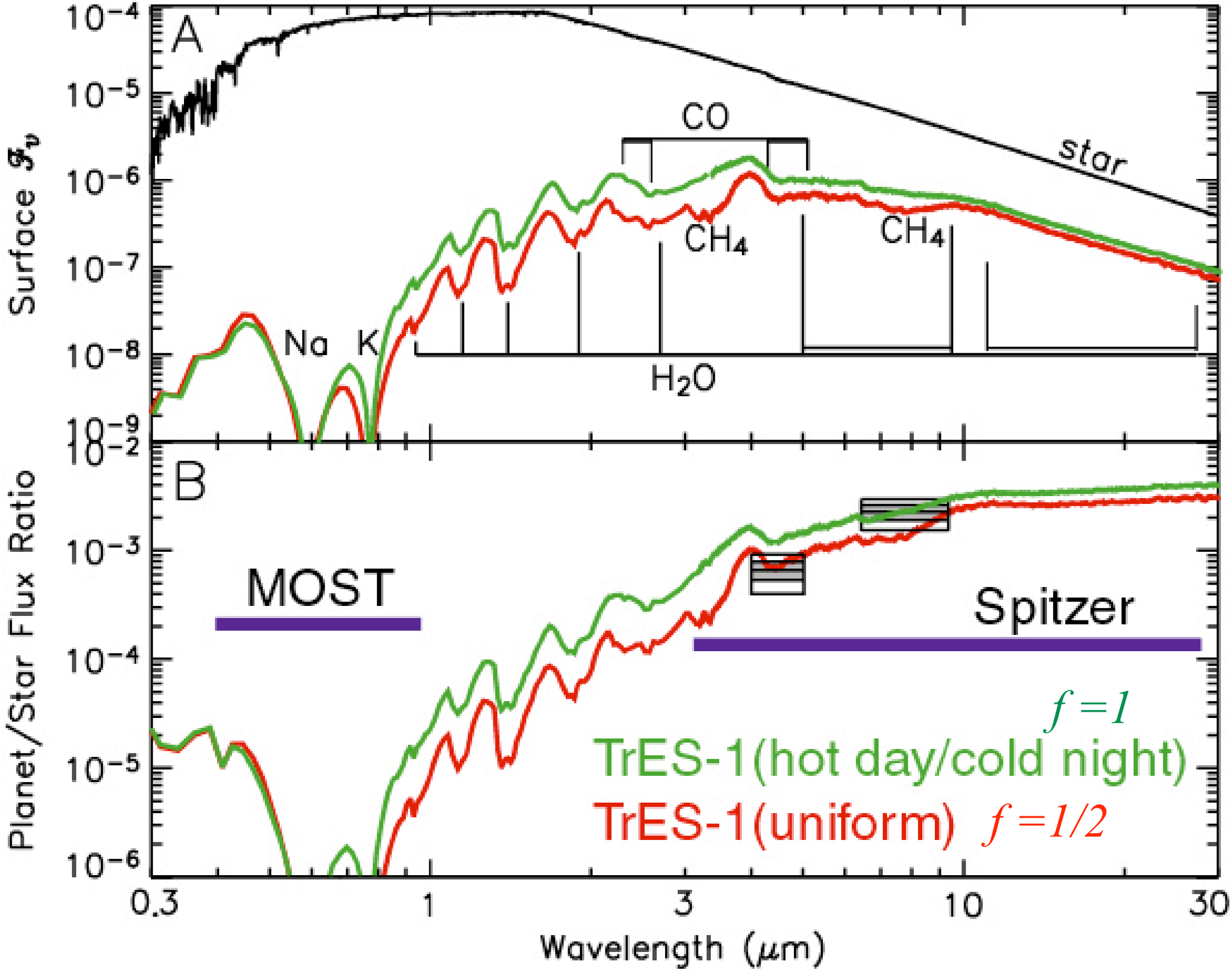

Fortney et al.(2005)
Barman et al.(2005)
Iro et al.(2005)
CH4\CO
MgSiO3
Fe
Mg2SiO4
Na2S
P (bar)
T (K)
10−4
10−3
10−2
10−1
100
101
102
103
500
1000
1500
2000
2500
3000

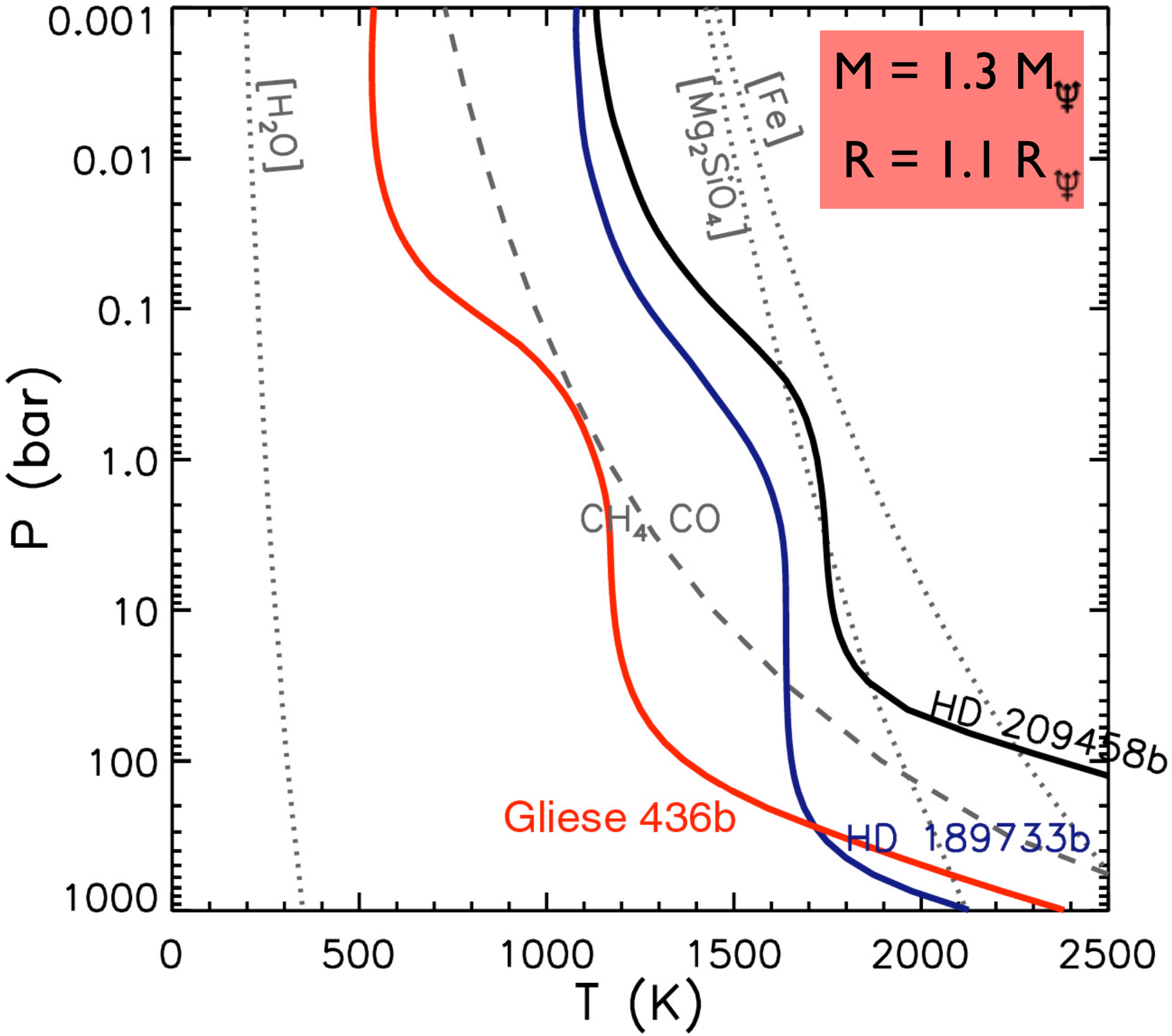




Radiative timescales are shorter than dynamical timescales!


A
B
Surface g_ν
Planet/Star Flux Ratio
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
CO
star
CH_4
CH_4
Na
K
H_2O
MOST
Spitzer
$f=1$
TrES-1(hot day/cold night)
TrES-1(uniform) $f=1/2$
0.3
1
3
10
30
Wavelength (μm)

Gliese 436b


M = 1.3 M⊕
R = 1.1 R⊕
[H2O]
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CH4, CO
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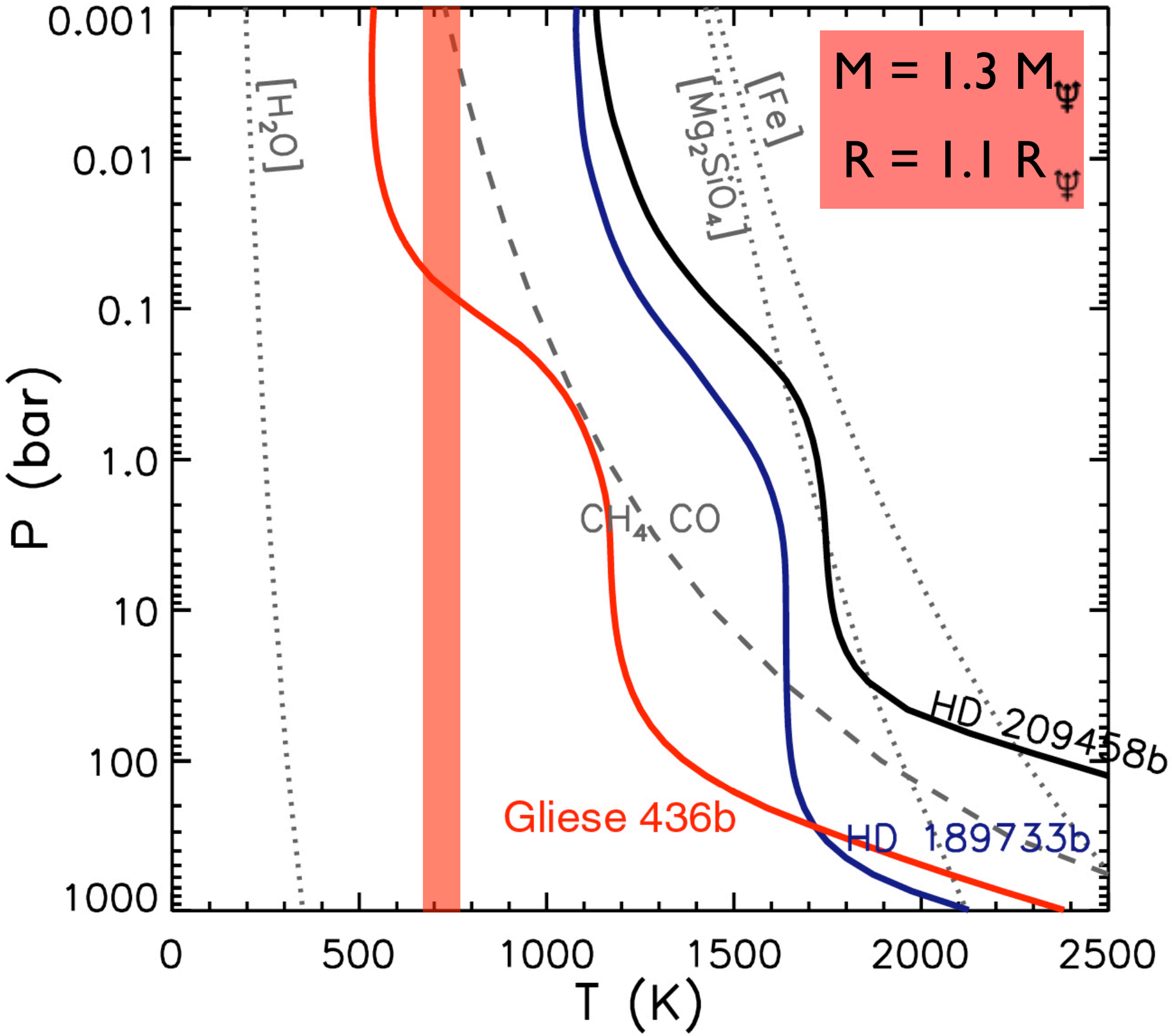
P (bar)
T (K)
0.001
0.01
0.1
1.0
10
100
1000
0
500
1000
1500
2000
2500

Gliese 436b

T_{brt} (8μm) = 712 ± 36 K

Deming et al. (2007)



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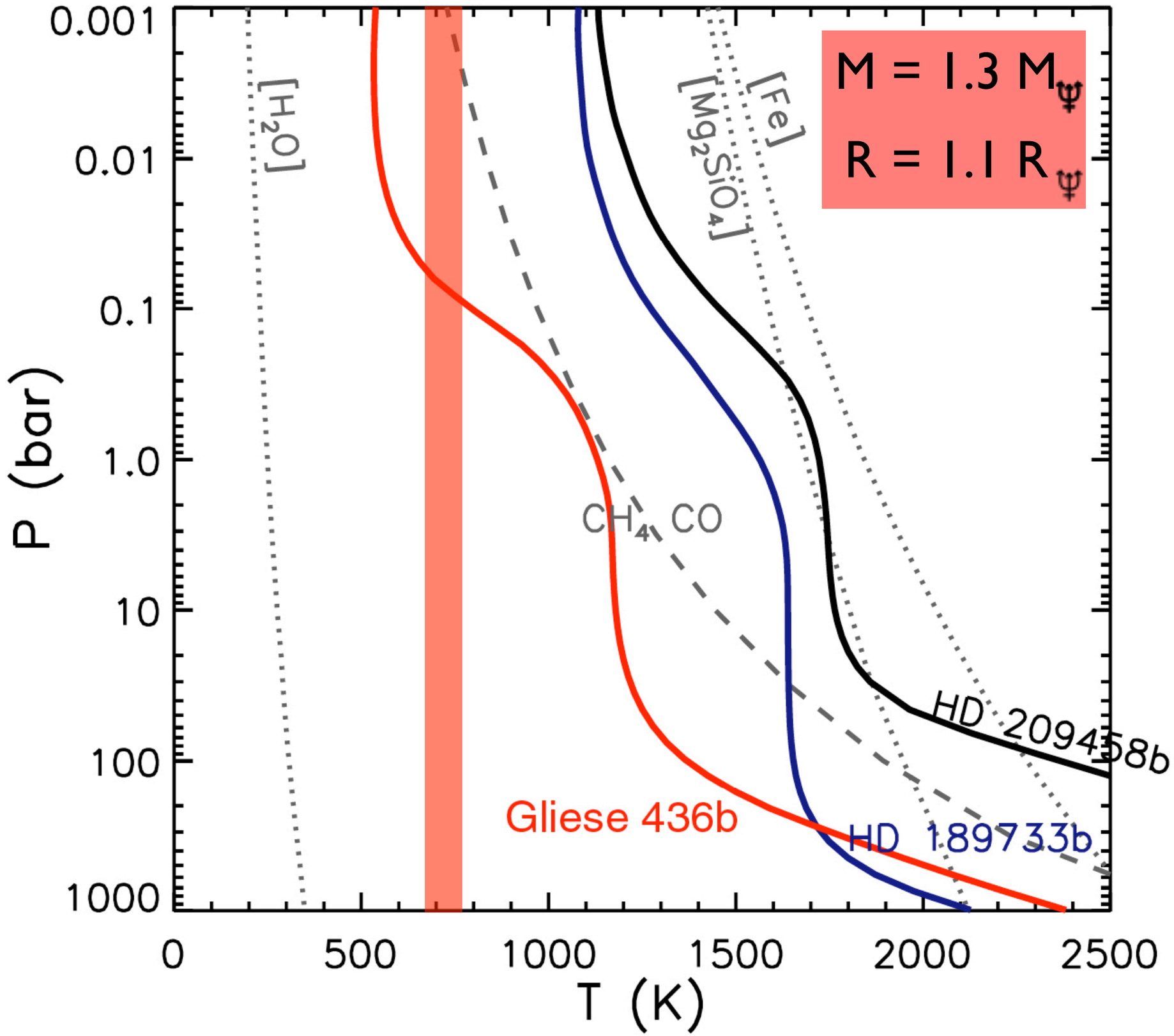
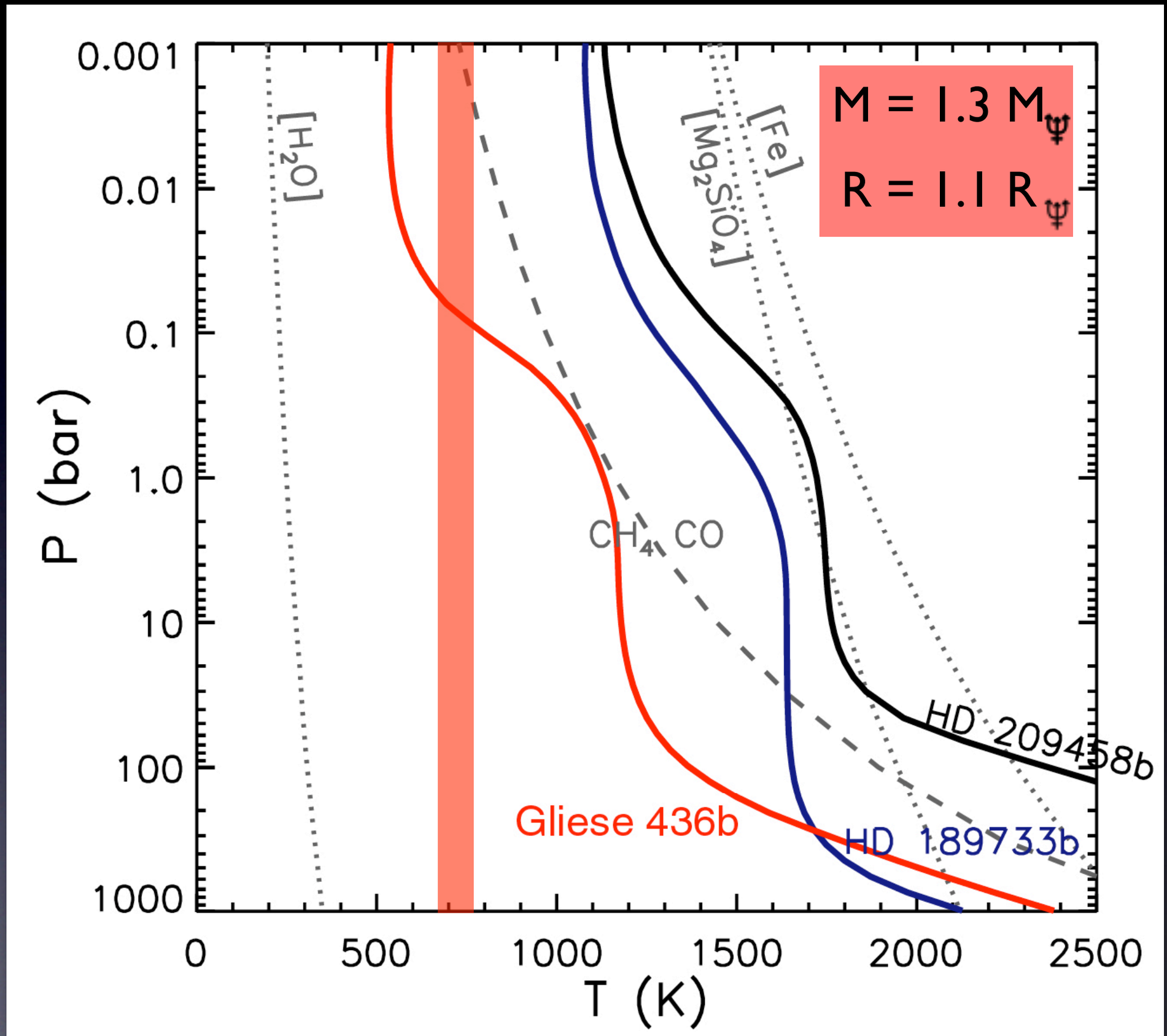
$T_{eq} \approx 640$ K





Gliese 436b

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Deming et al. (2007)

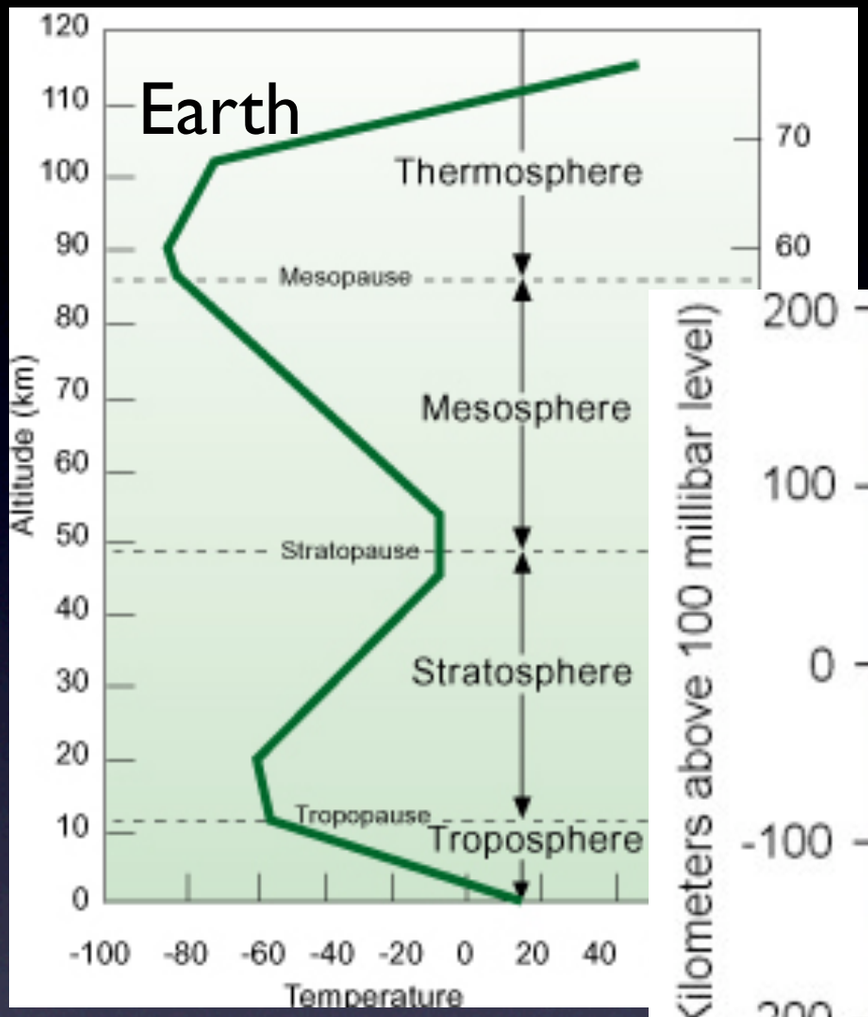
$T_{eq} \approx 640$ K

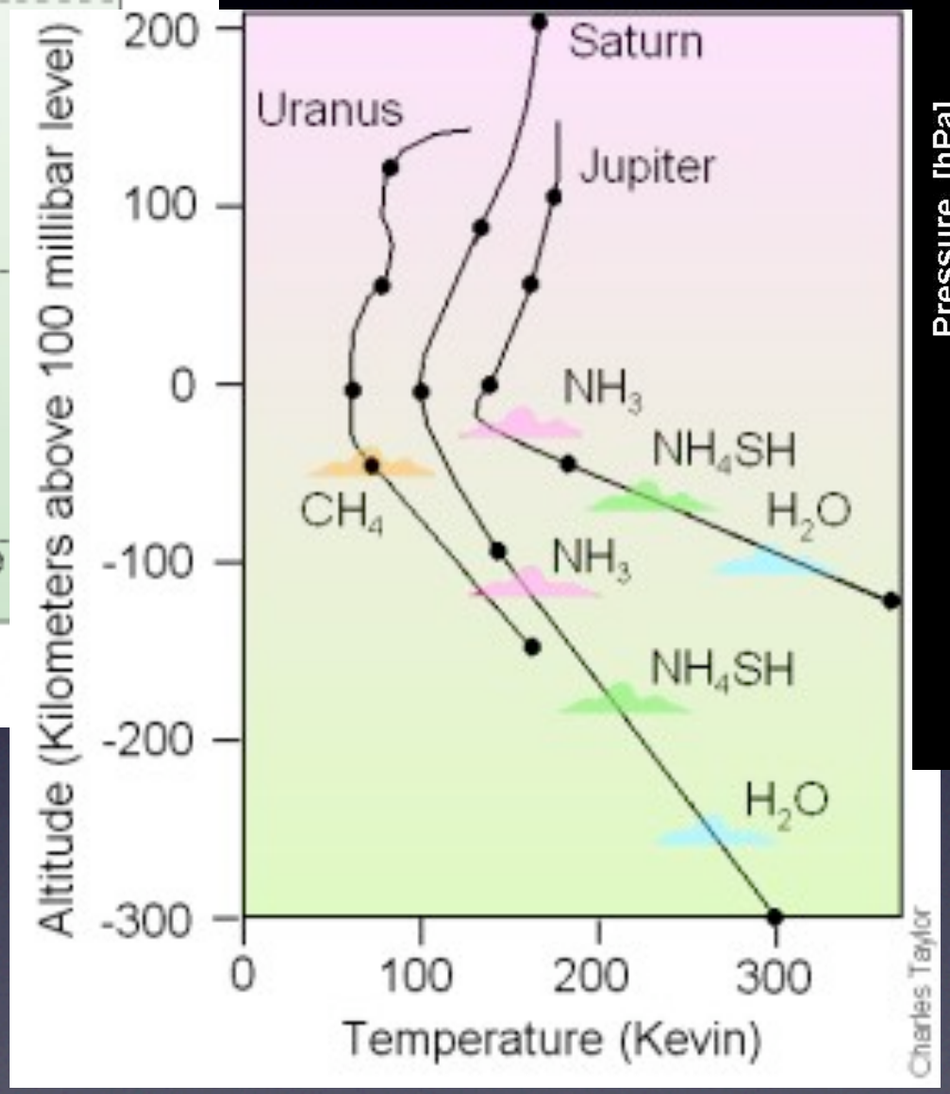
But...

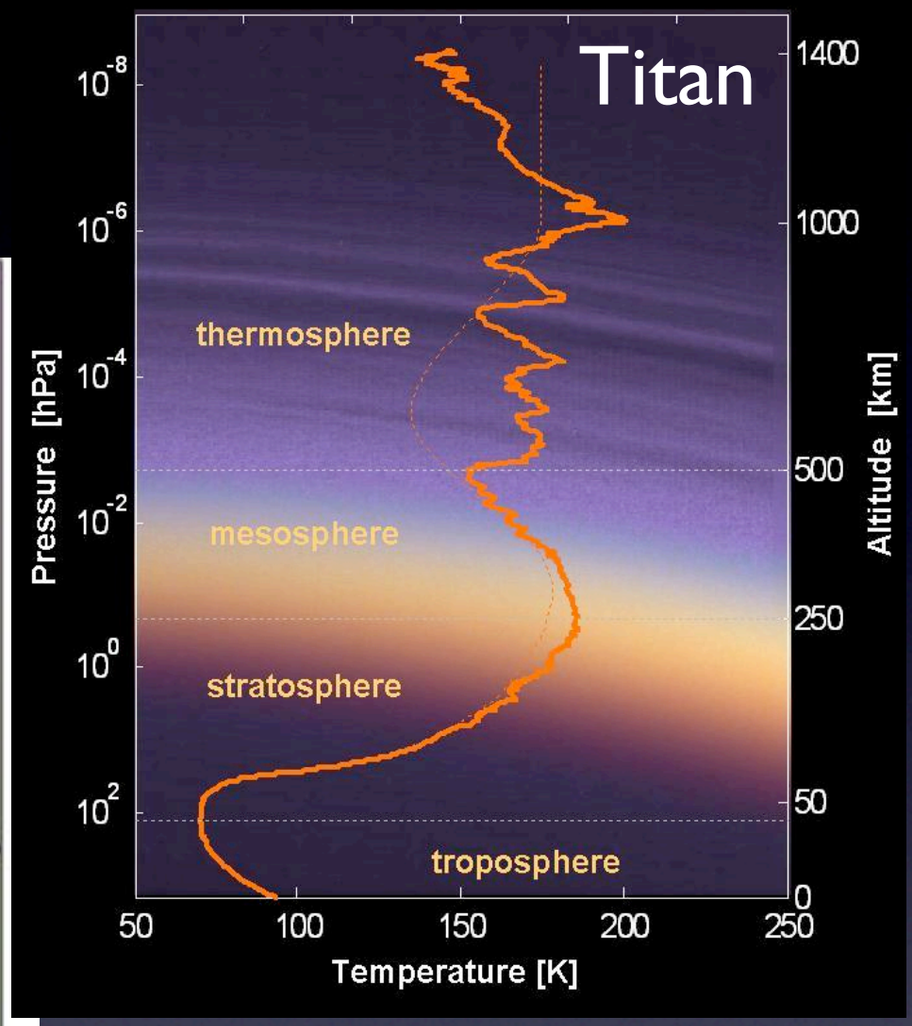
$T_{brt} \neq T_{eff} \neq T_{eq}$

Stratospheres

Warm Stratospheres

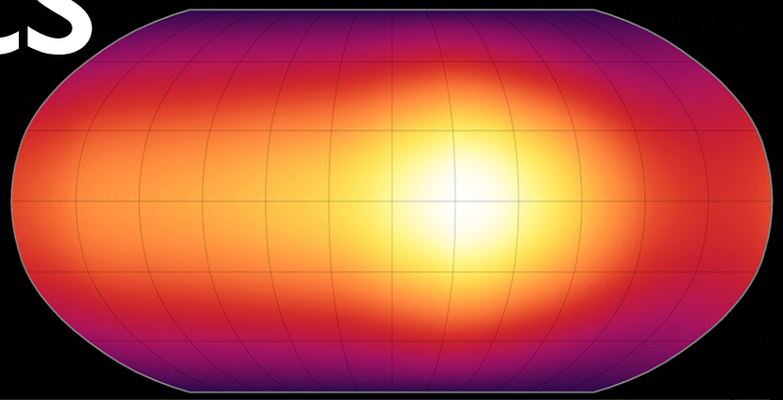




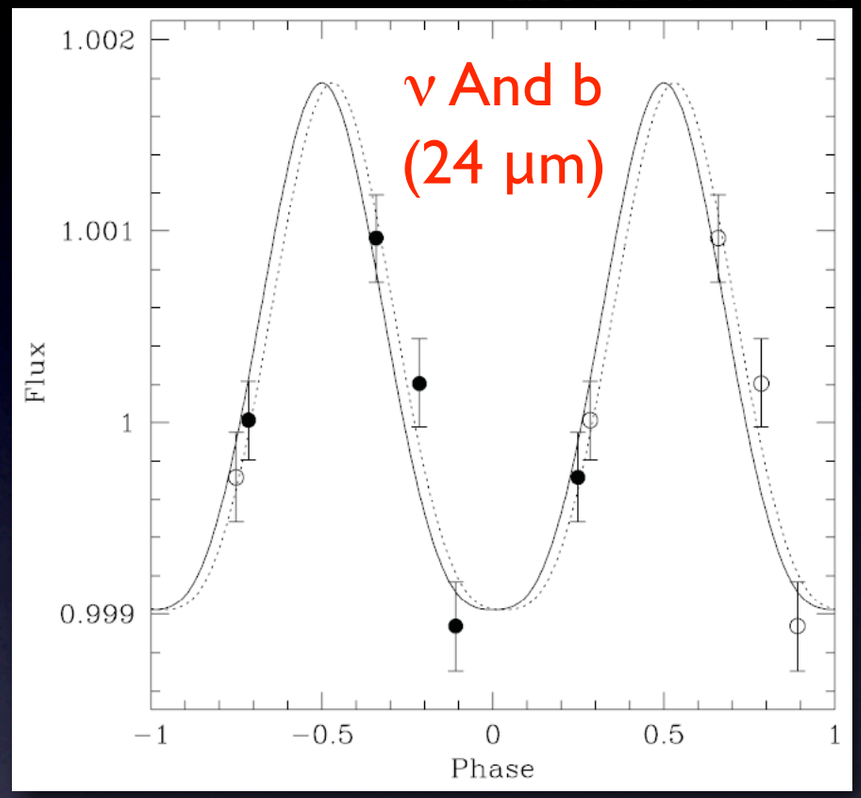


Photochemistry is important in every case.

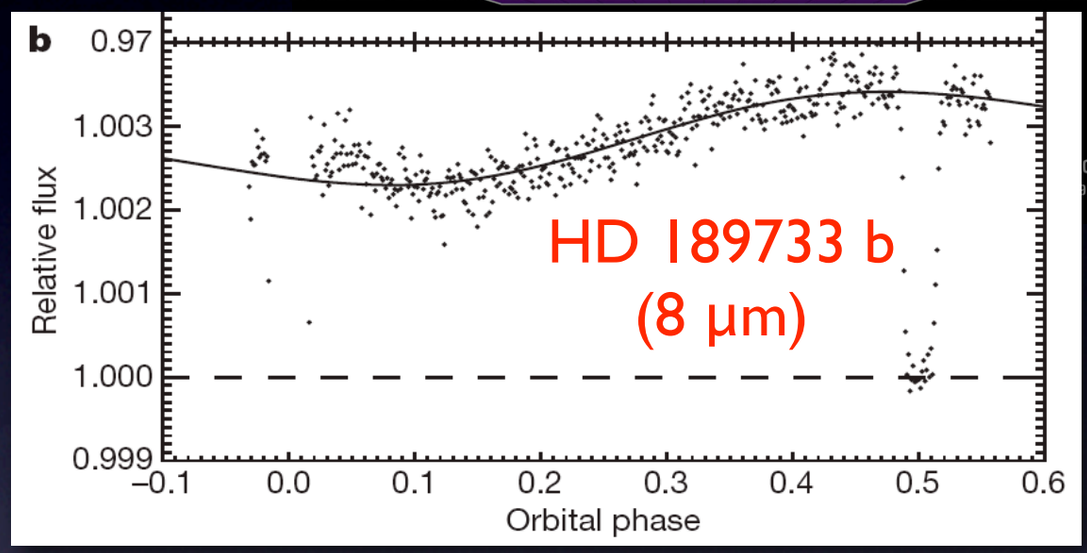
Diversity of Planets



also HD 179949b



Harrington et al. (2006)



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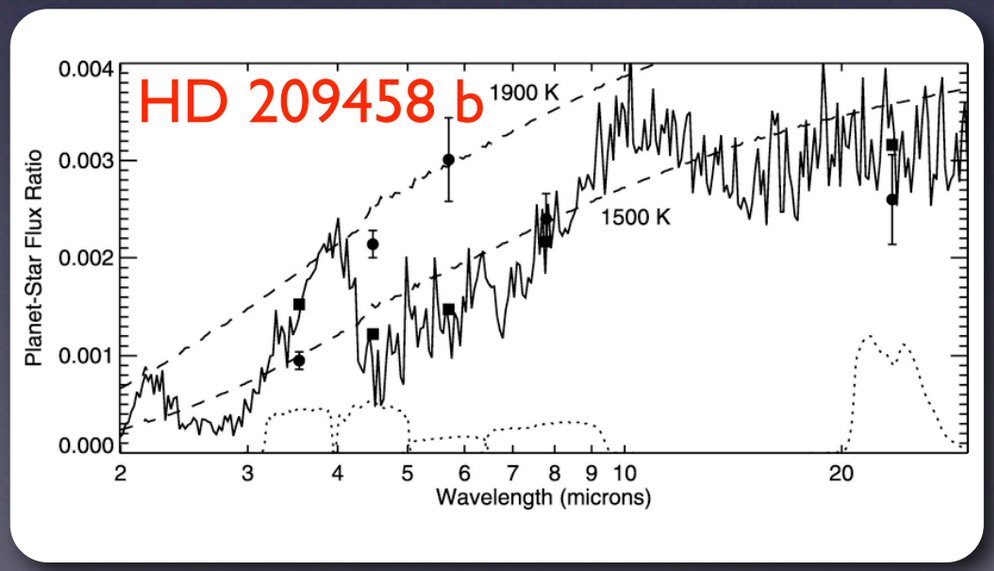
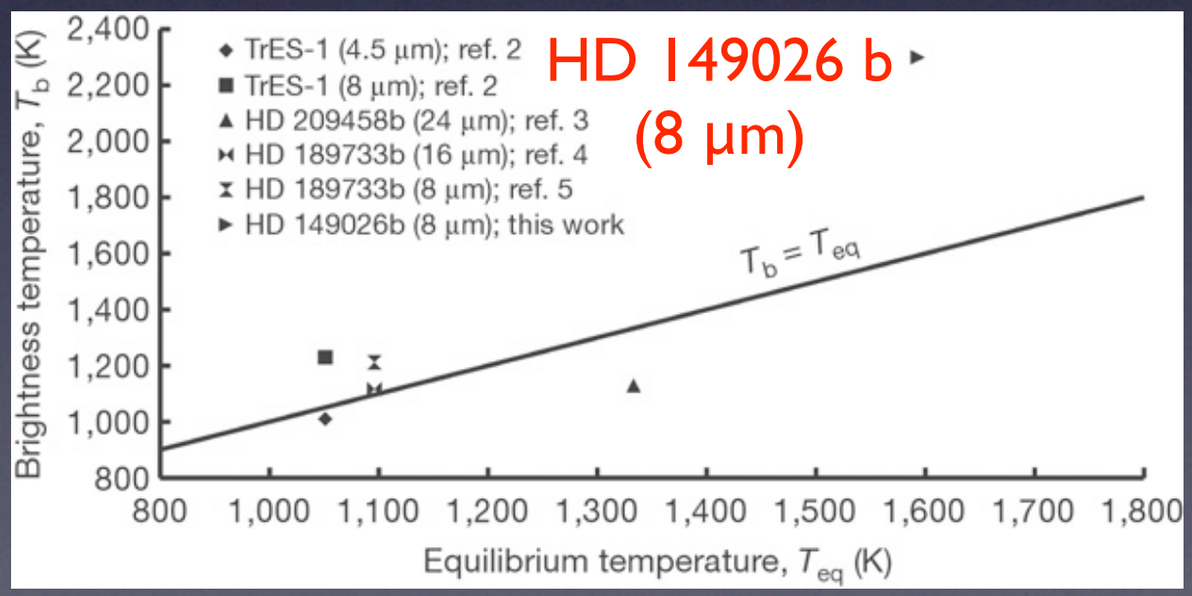


Knutson et al. (2008)



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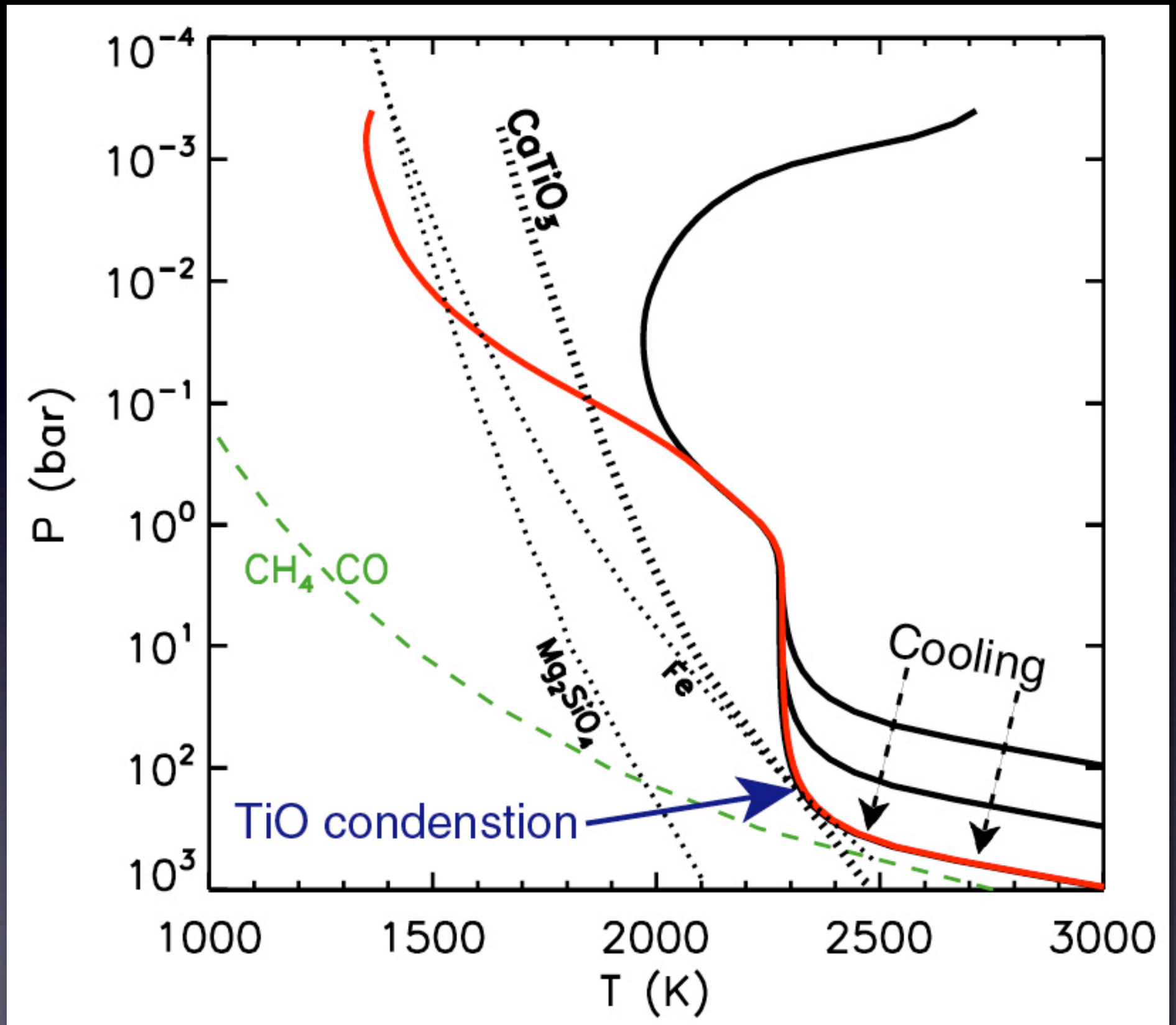
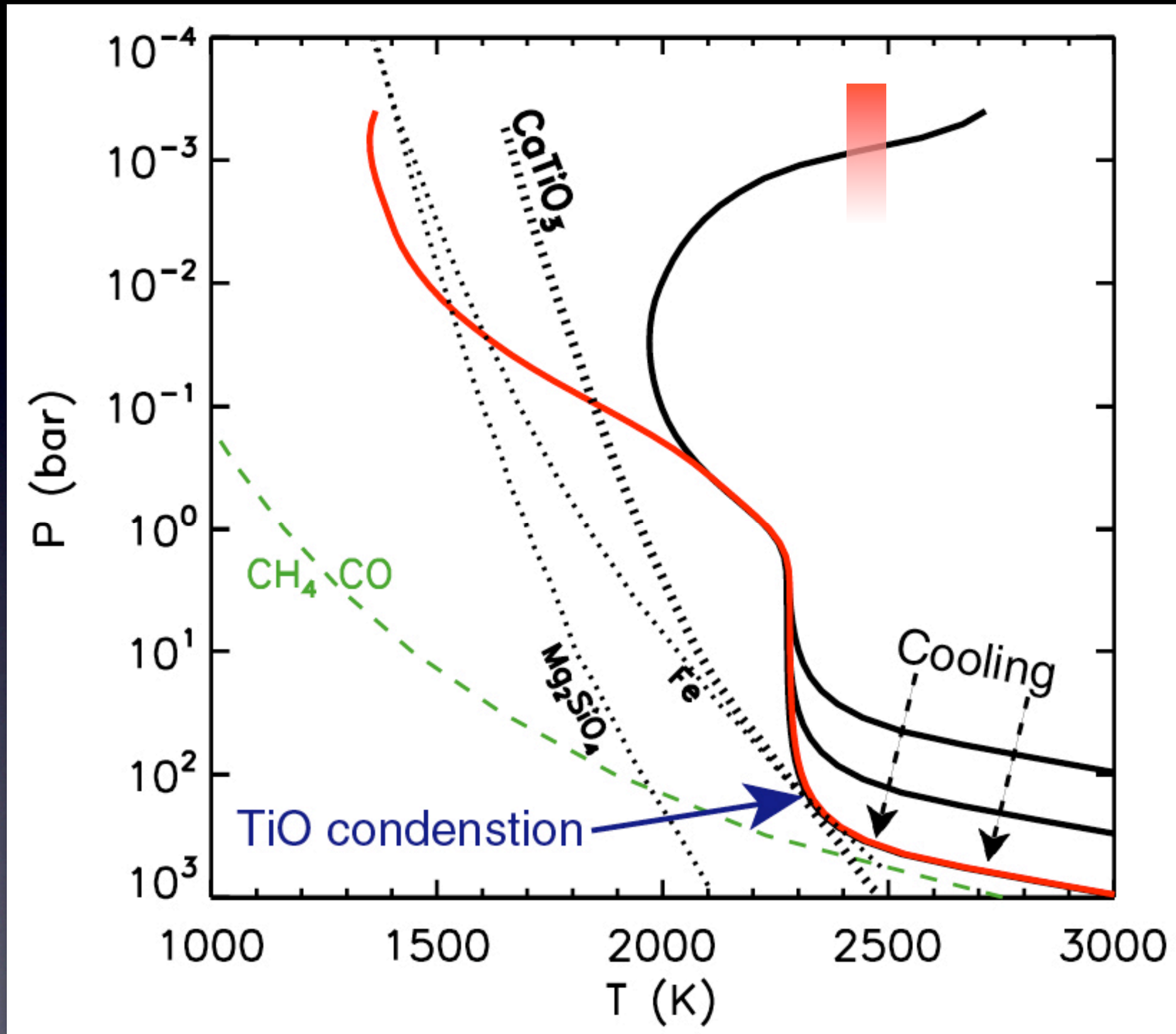

10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
P (bar)
1000
1500
2000
2500
3000
T (K)
$CaTiO_3$
CH_4 CO
Mg_2SiO_4
Fe
Cooling
TiO condenstion


10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
P (bar)
1000
1500
2000
2500
3000
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$CaTiO_3$
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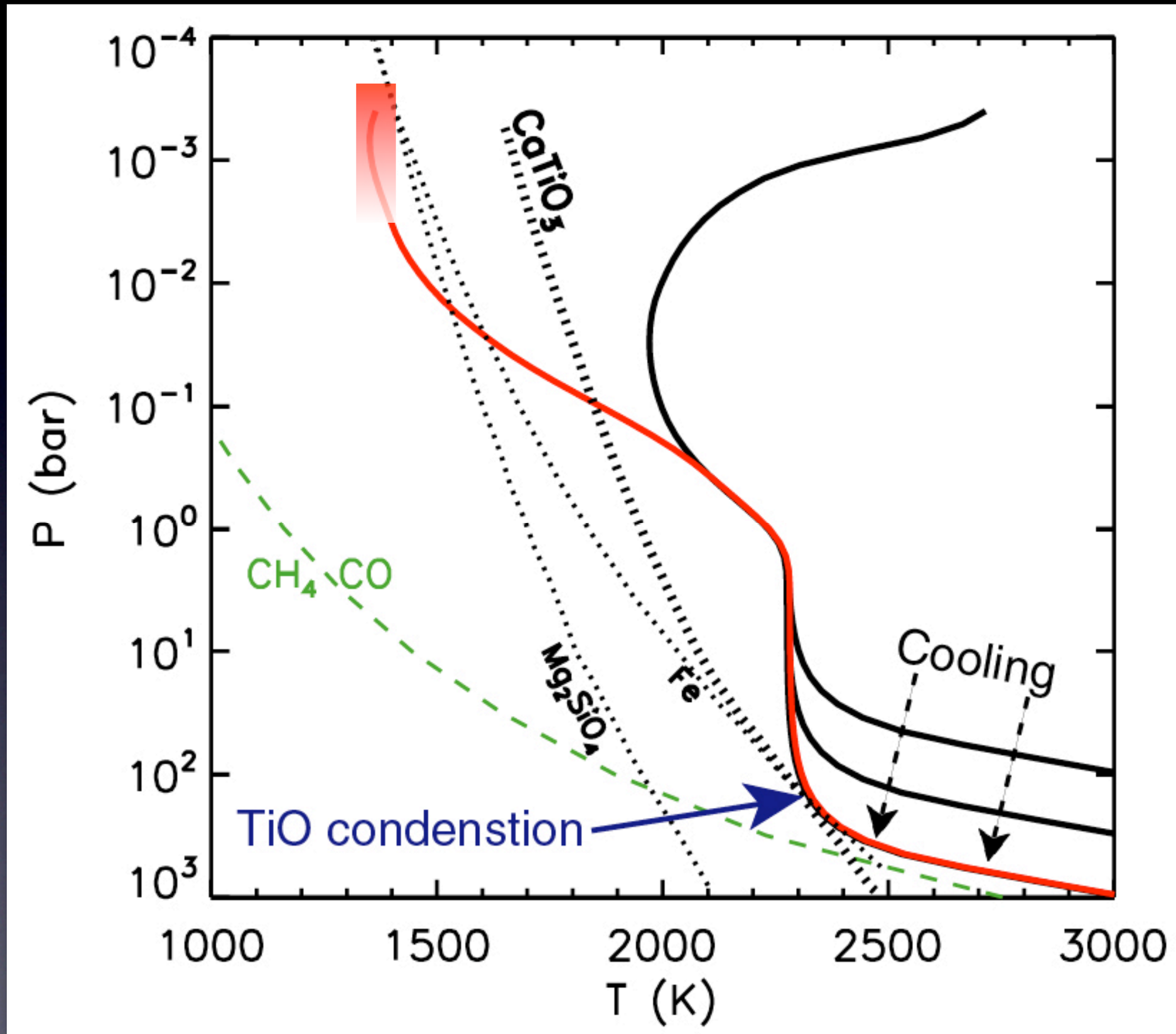
Cooling


10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
P (bar)
1000
1500
2000
2500
3000
T (K)
$CaTiO_3$
CH_4 CO
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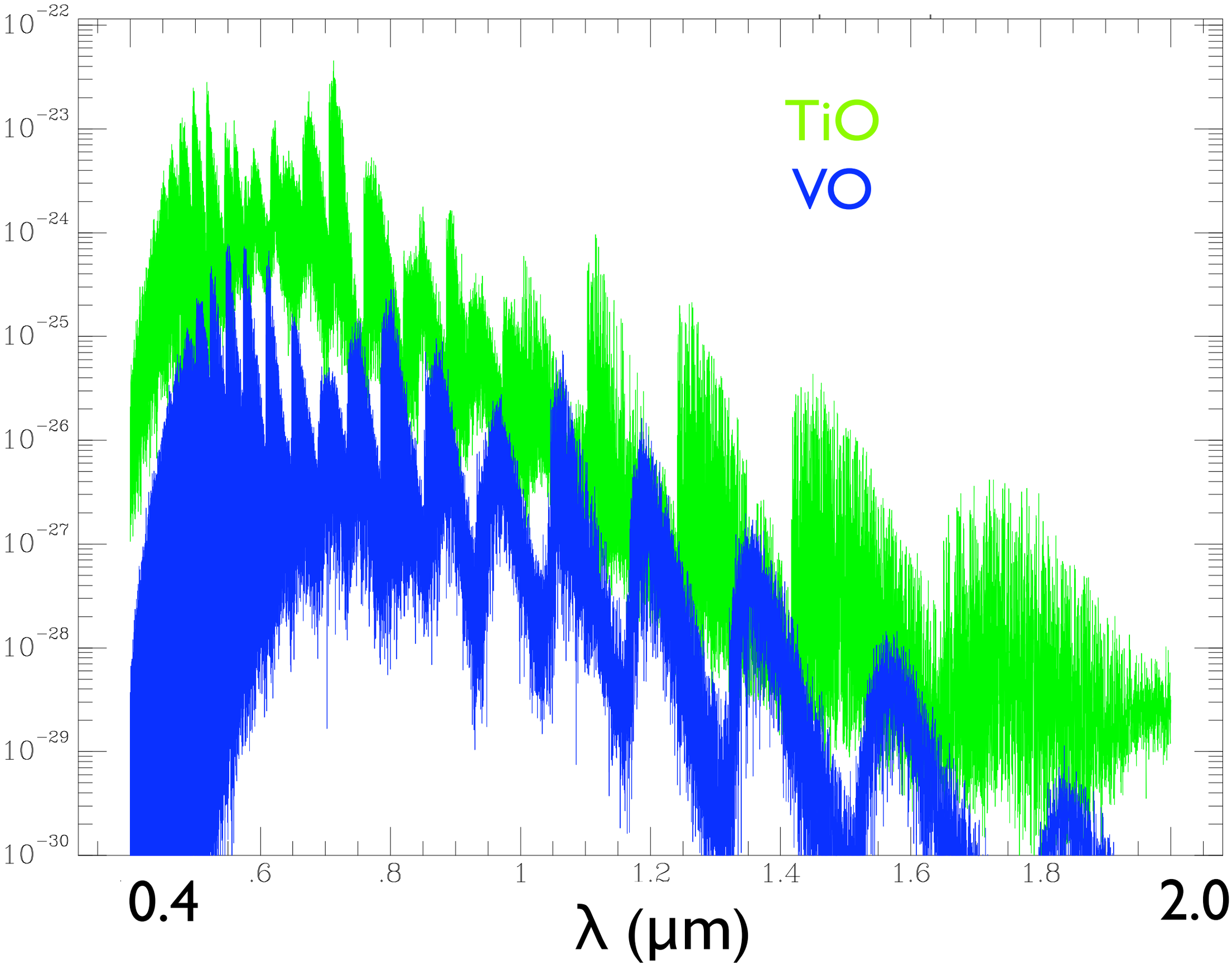
Cooling
TiO condenstion

K


TiO
VO
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
.6
.8
1
1.2
1.4
1.6
1.8

0.4

λ (μm)

2.0

κ

total opacity:
with TiO & VO
without

10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}

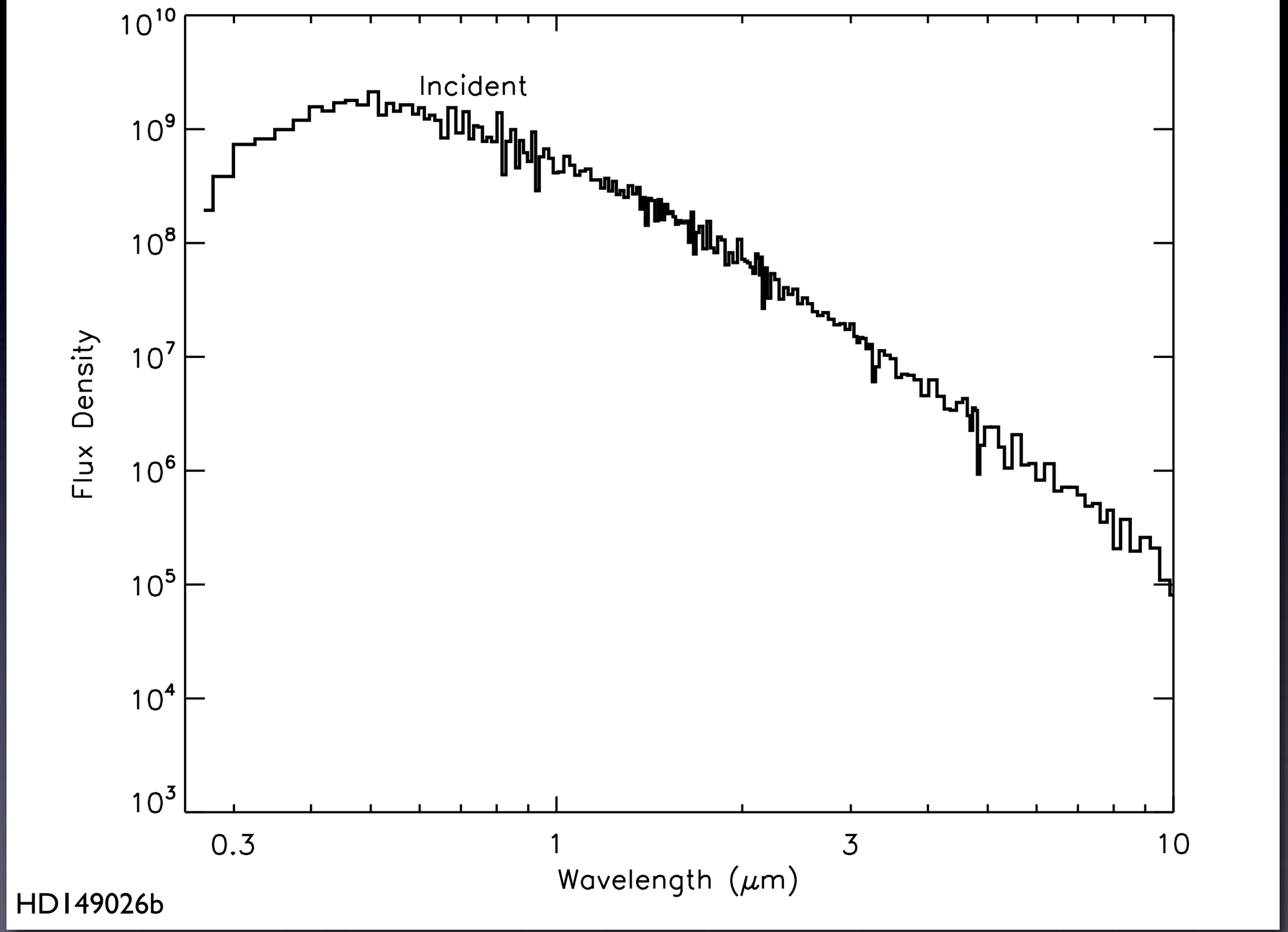
.6 .8 1 1.2 1.4 1.6 1.8

0.4

λ (μm)

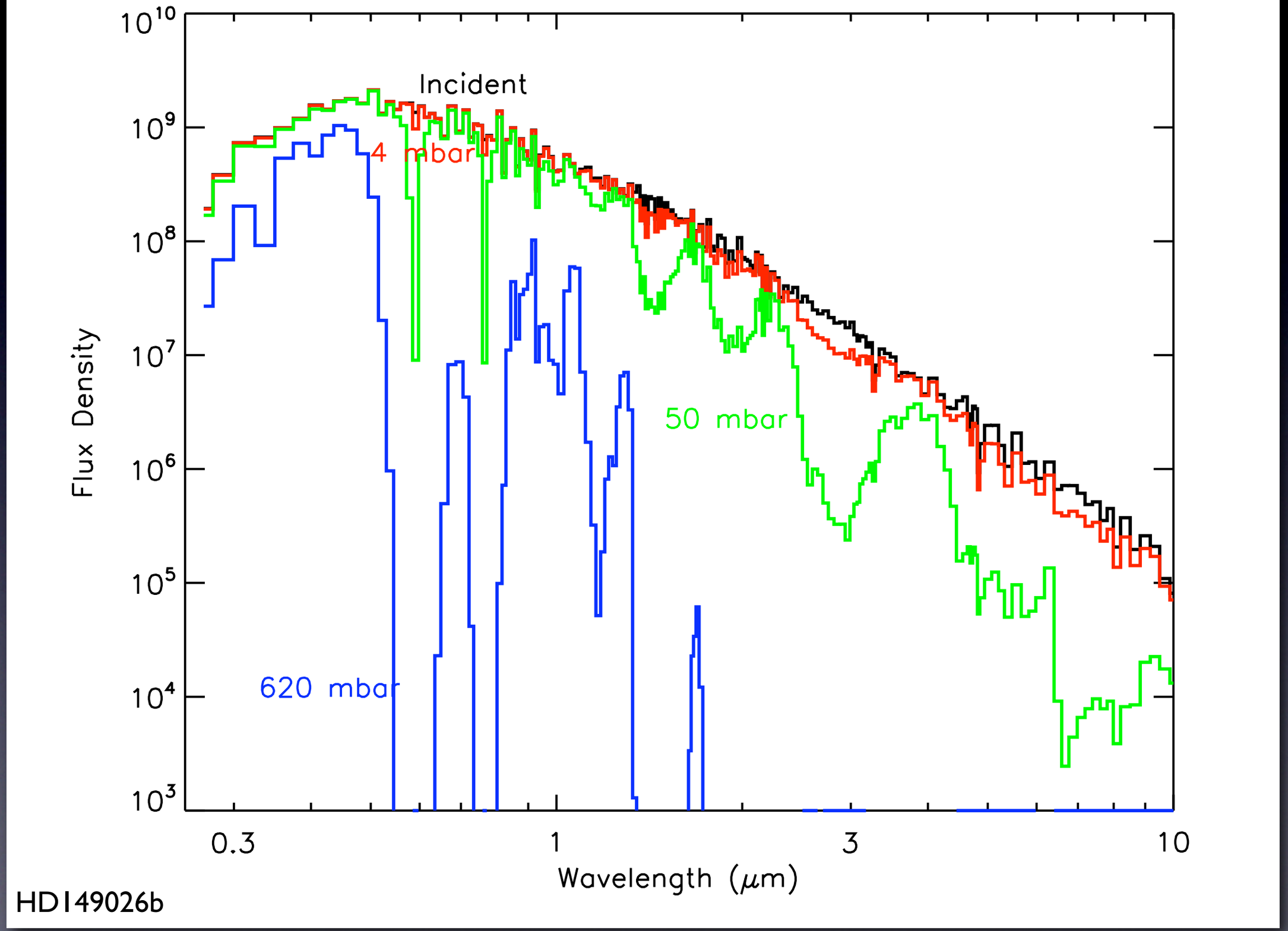
2.0

Downward Flux

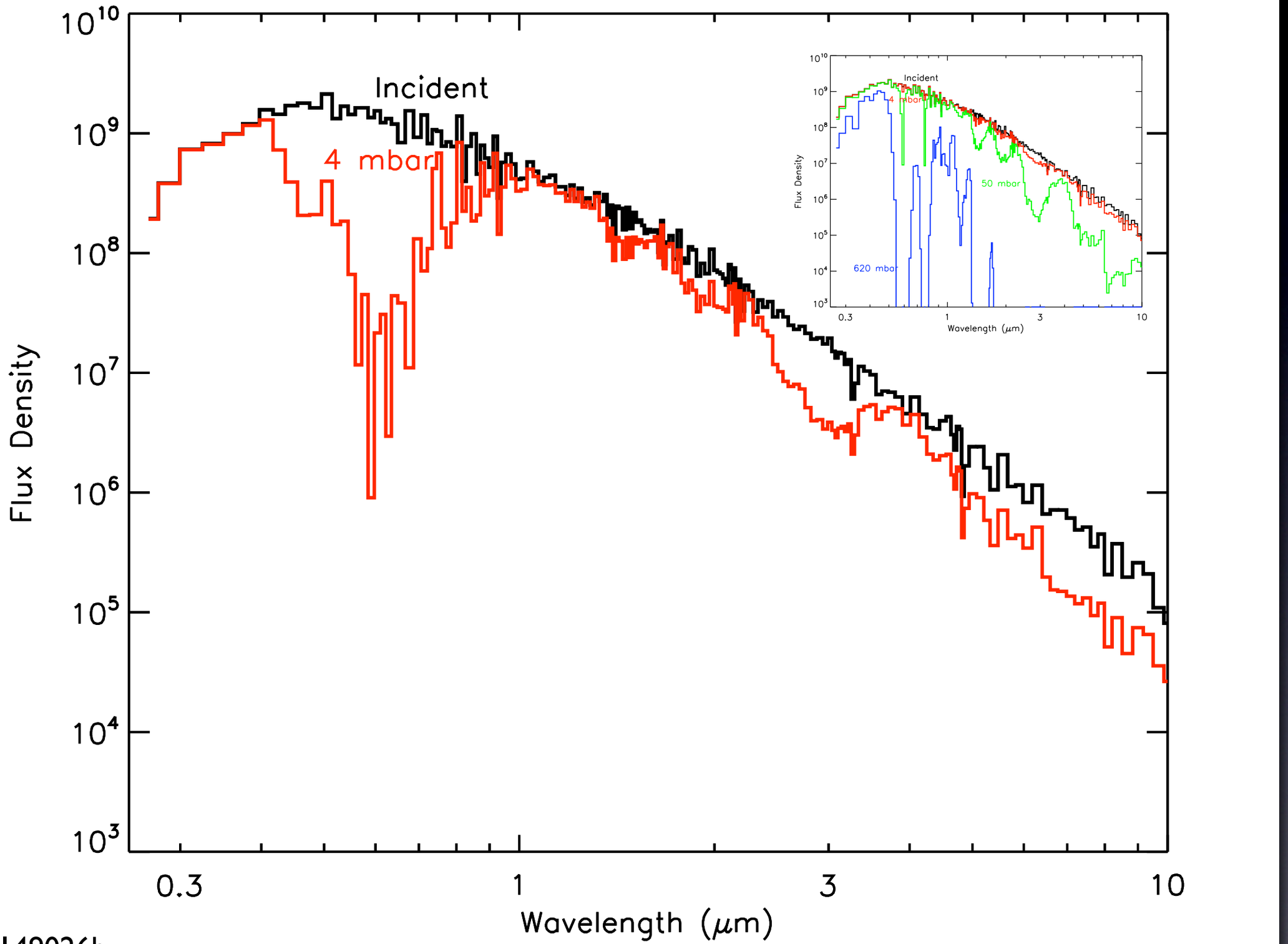


HD149026b

Downward Flux



Downward Flux



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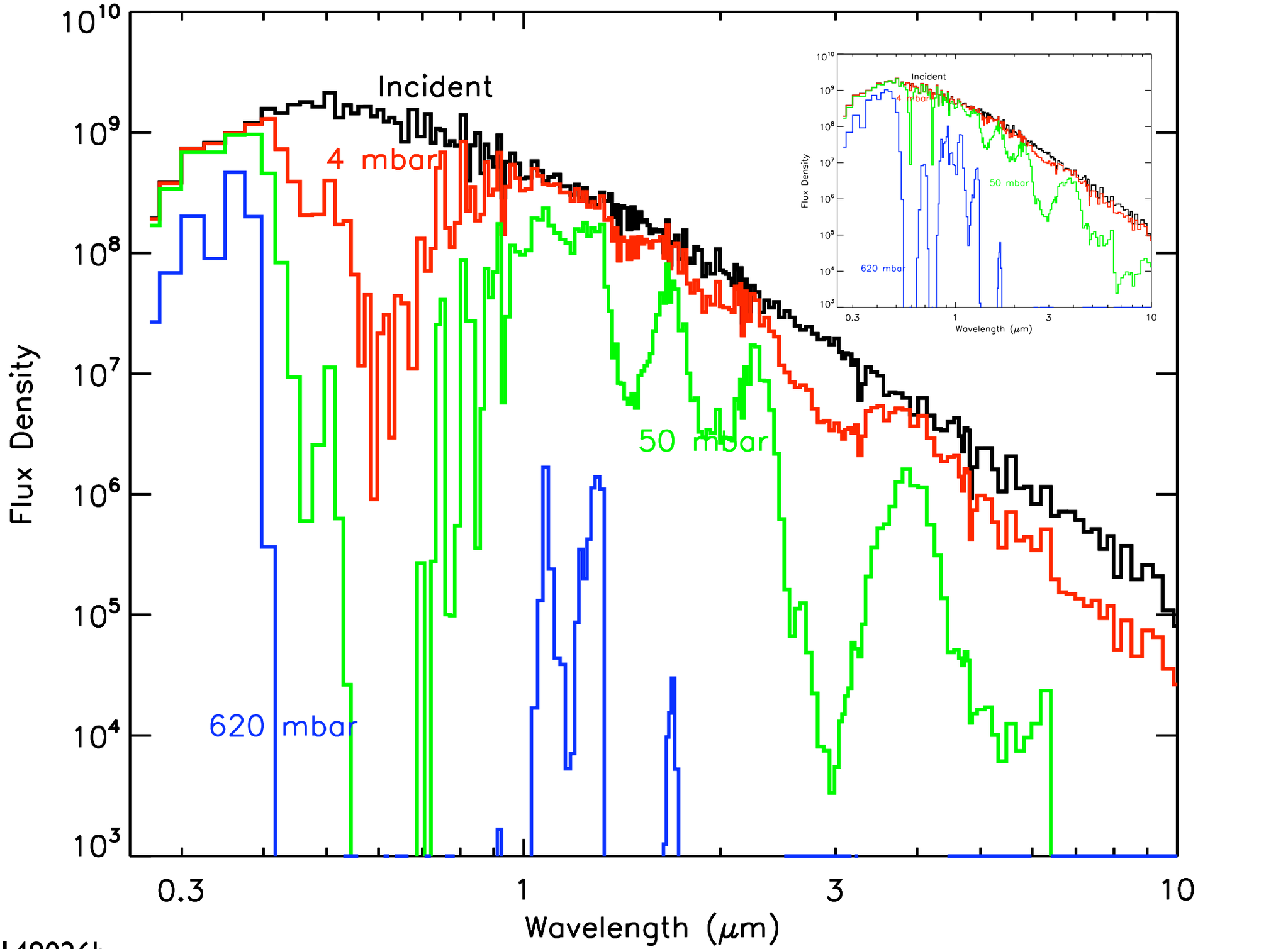
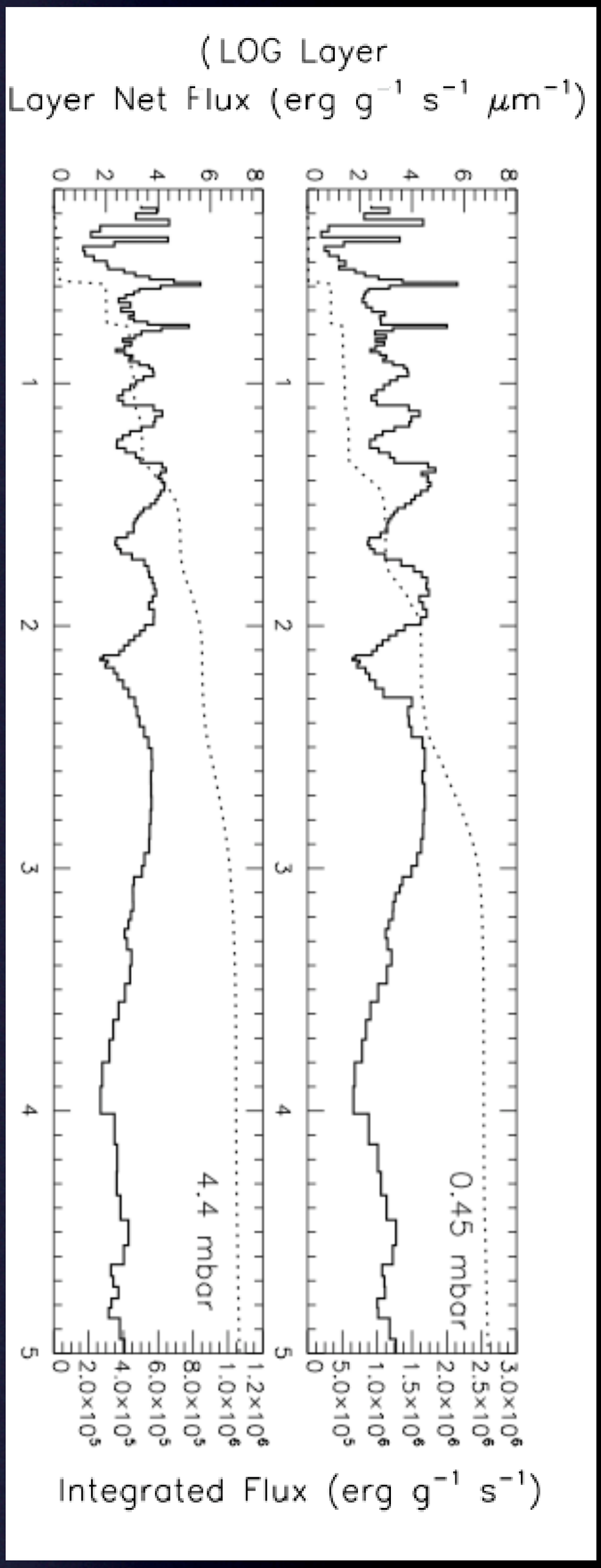
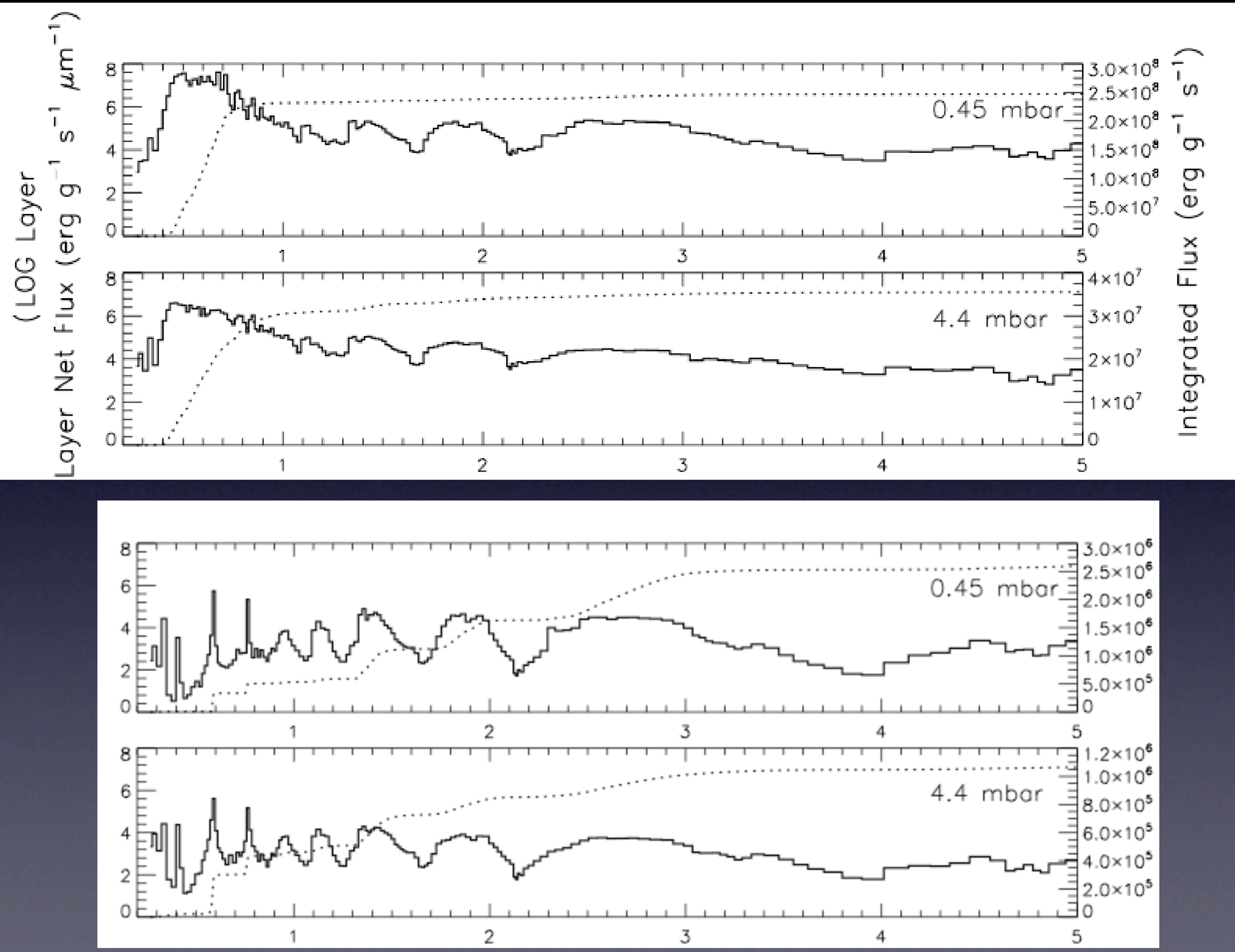
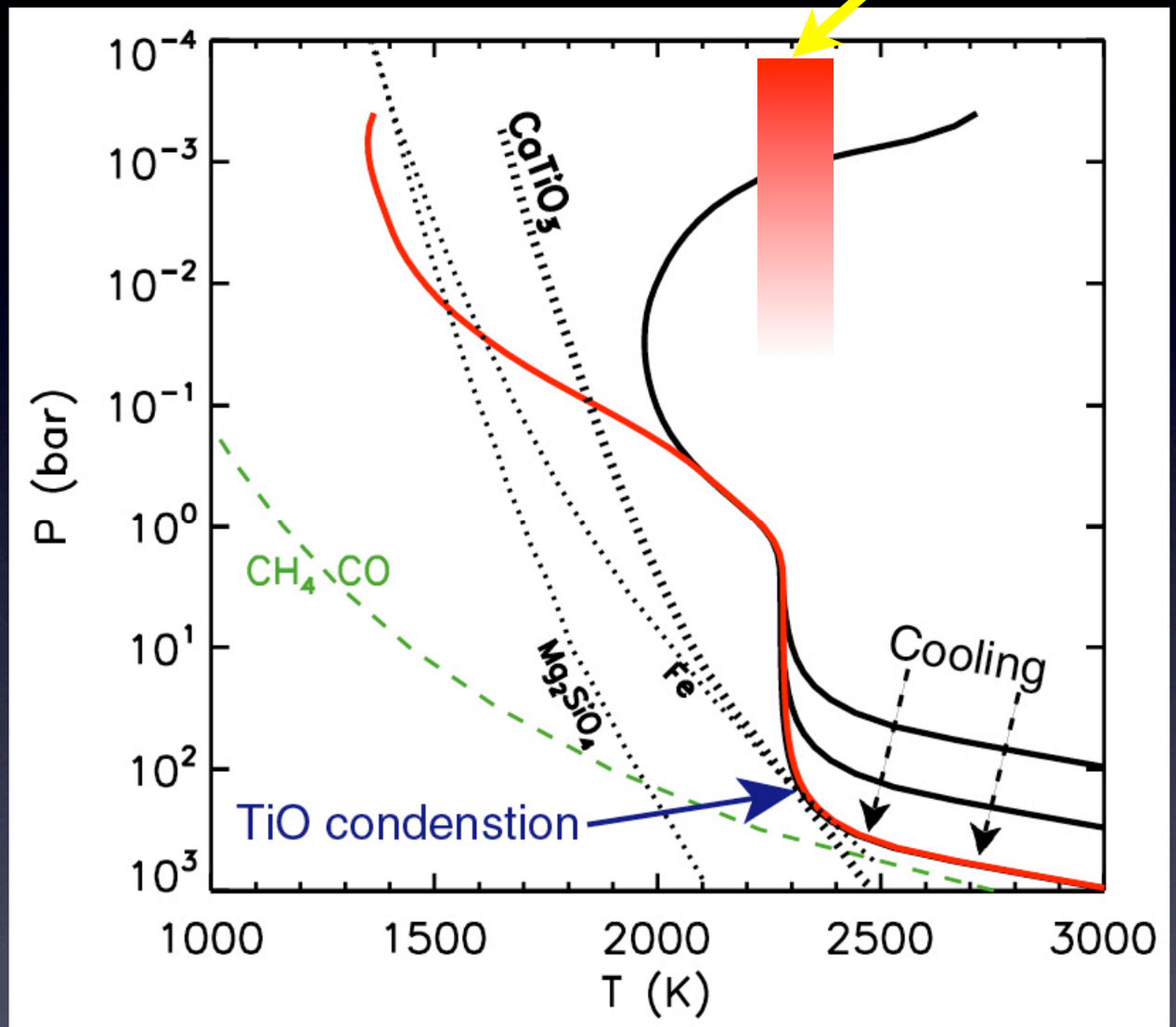
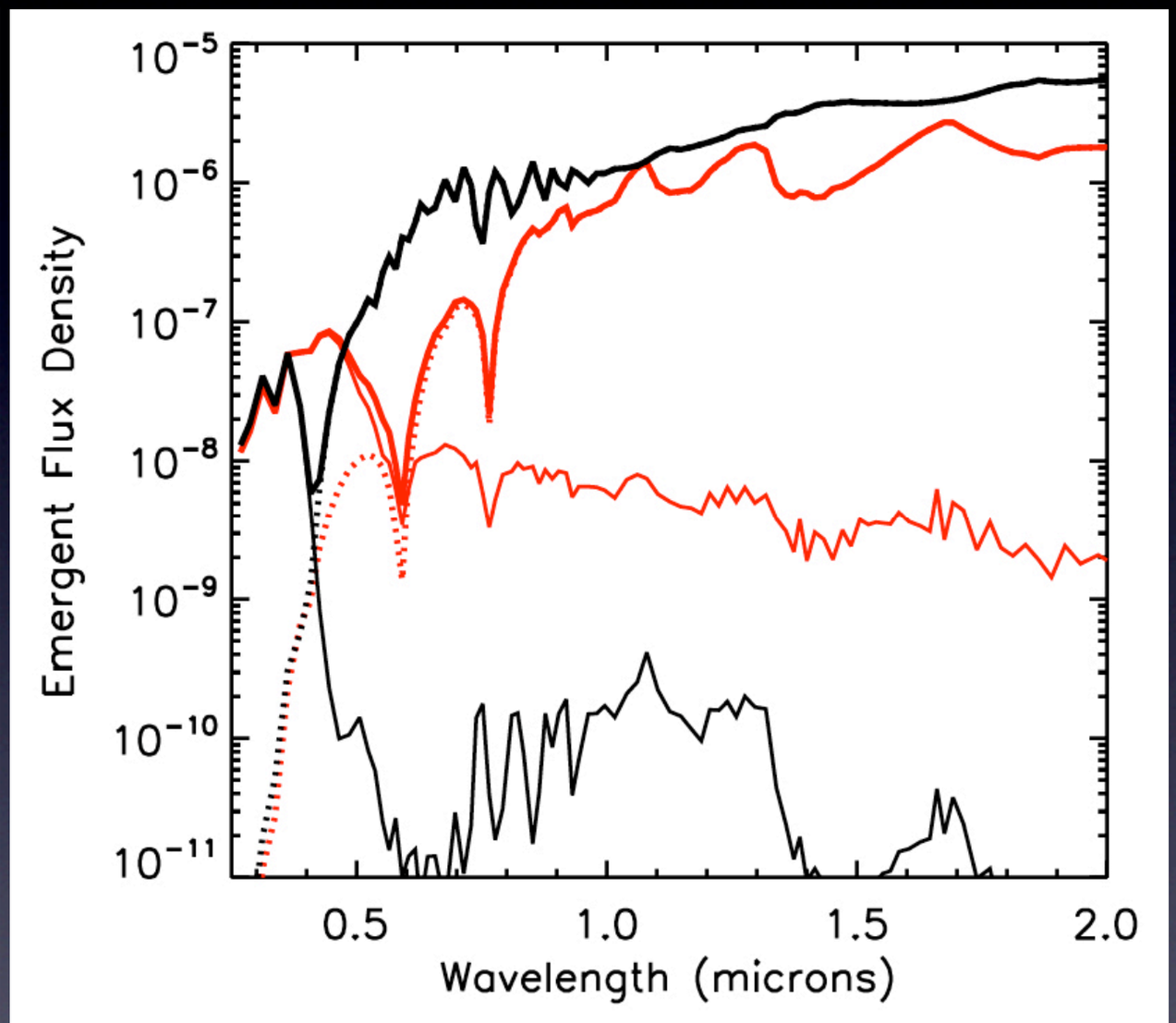


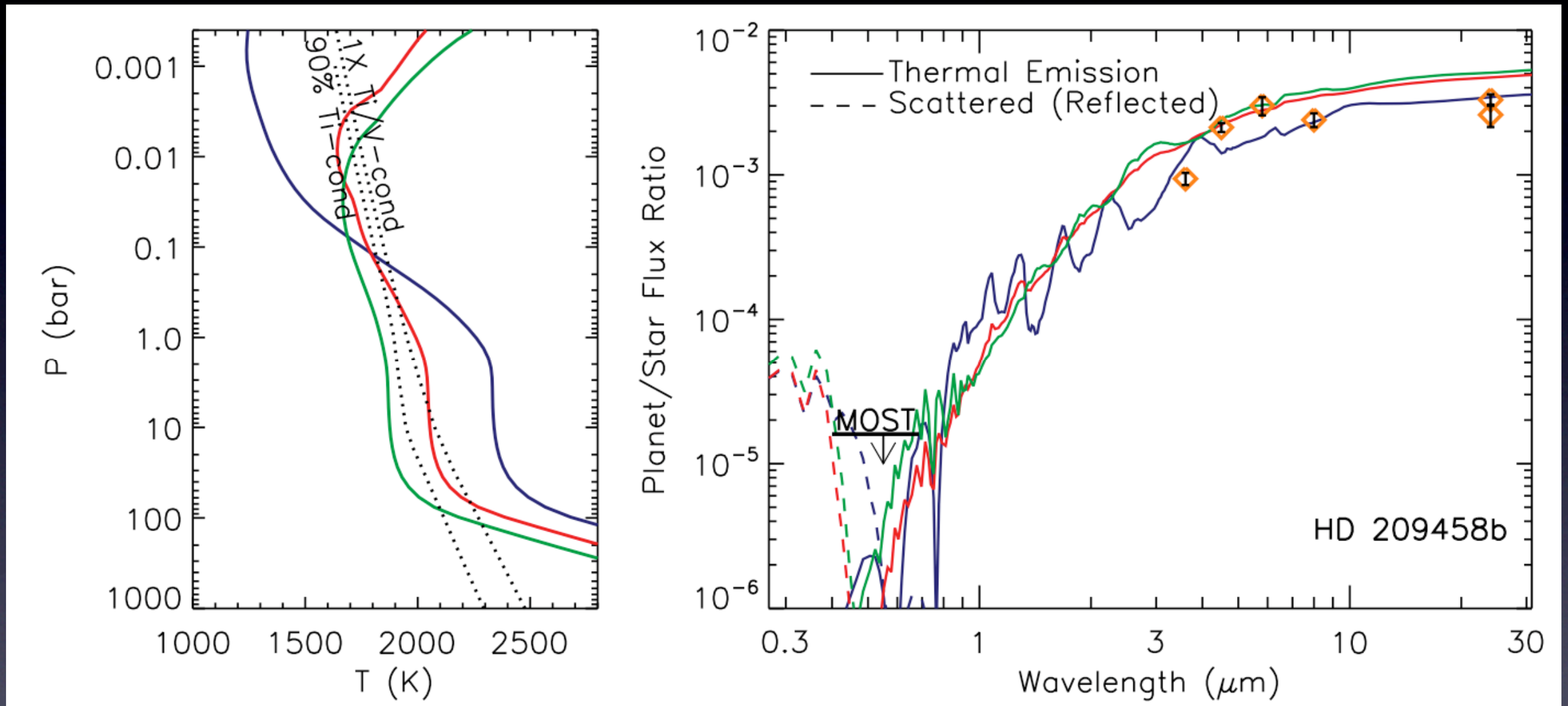

(LOG Layer
Layer Net Flux (erg g^{-1} s^{-1} μm^{-1})
0.45 mbar
4.4 mbar
Integrated Flux (erg g^{-1} s^{-1})


(LOG Layer Net Flux (erg g^{-1} s^{-1} μm^{-1})
Integrated Flux (erg g^{-1} s^{-1})
0.45 mbar
4.4 mbar
0.45 mbar
4.4 mbar

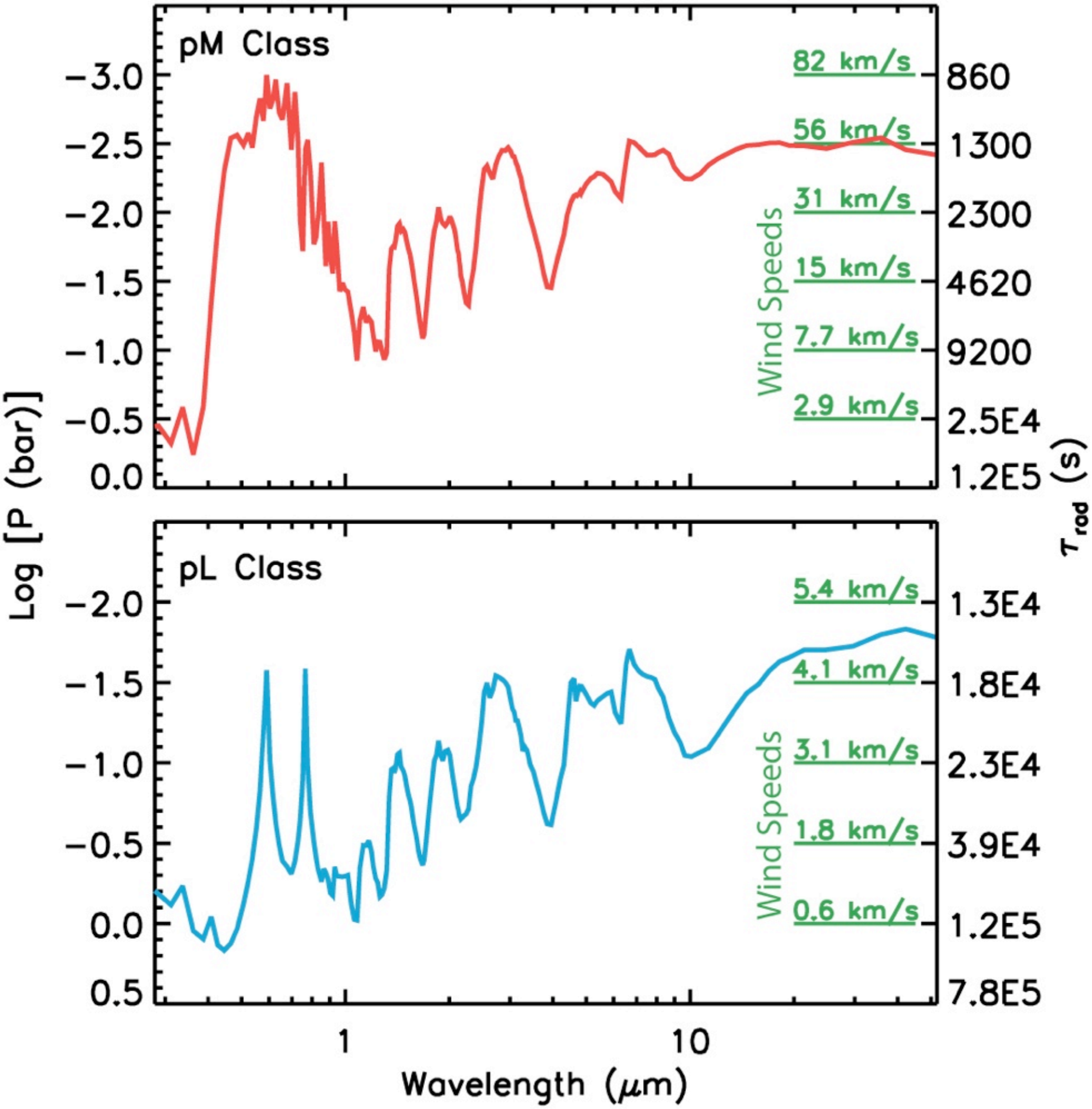
Harrington et al. (2007), for HD 149026b







Fortney et al. (2008)

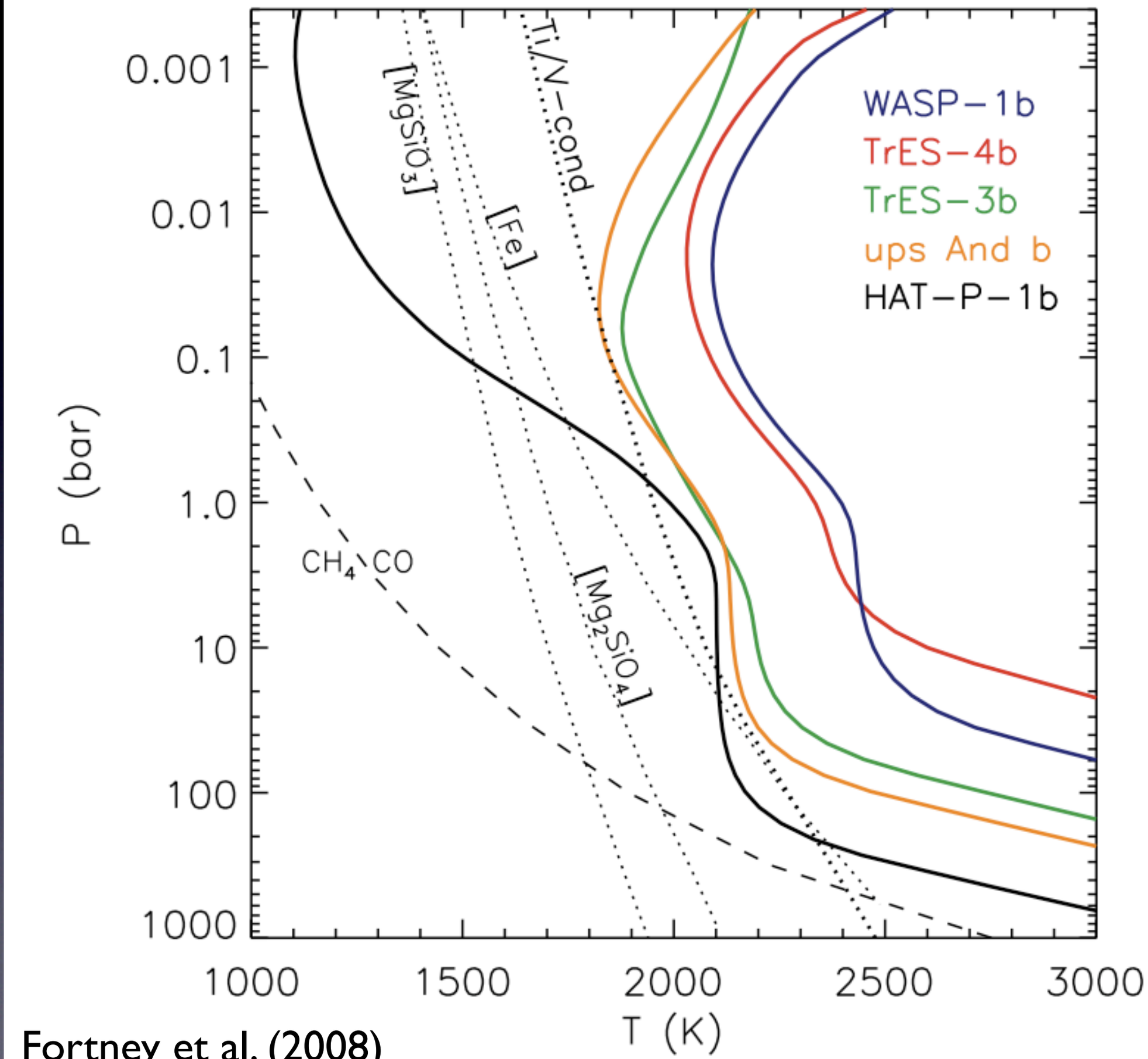


pM class

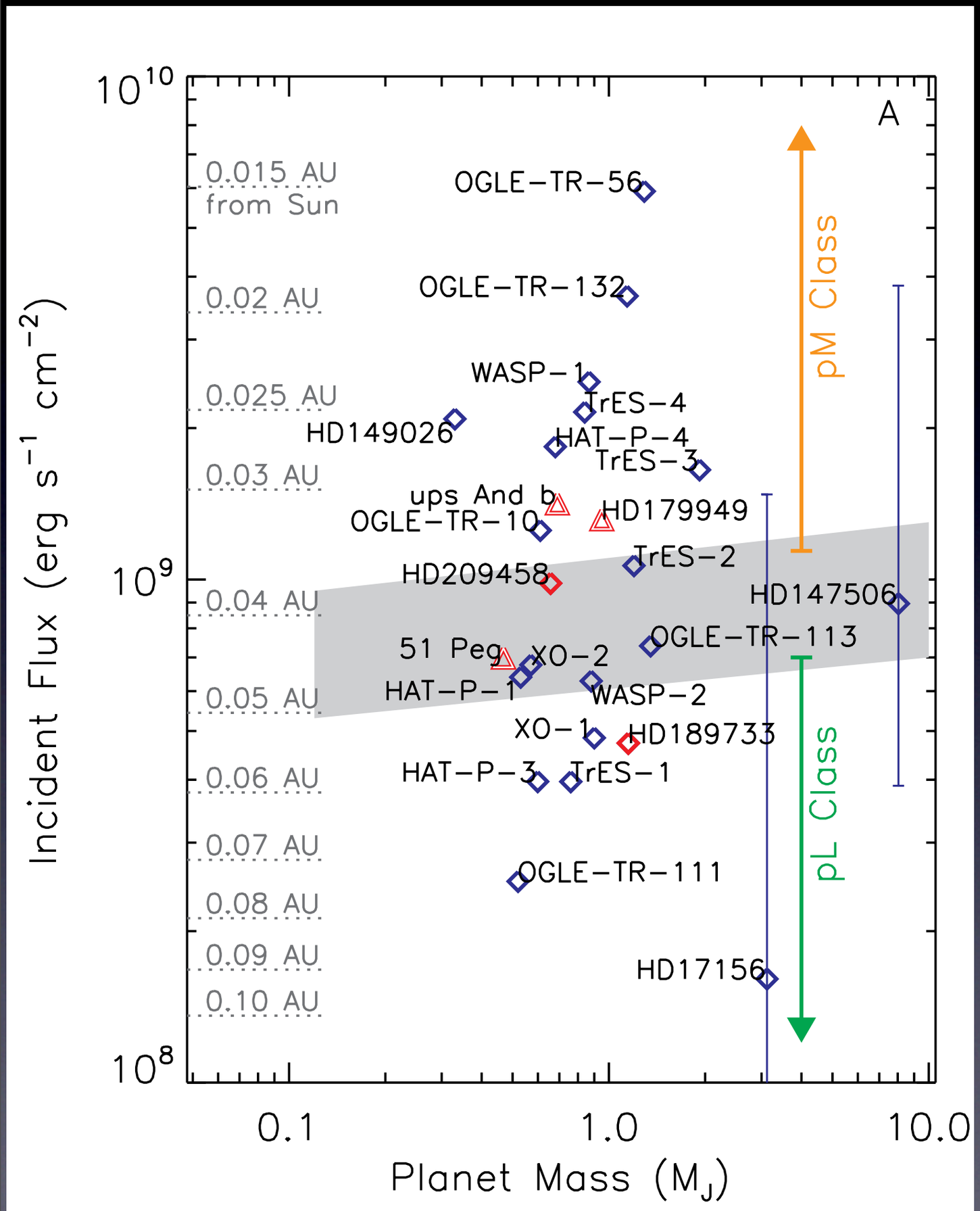
- TiO/VO stratospheres
- short T_{rad}
- hot/cold hemispheres

pL class

- cool upper atmospheres
- long T_{rad}
- more homogeneous hemispheres



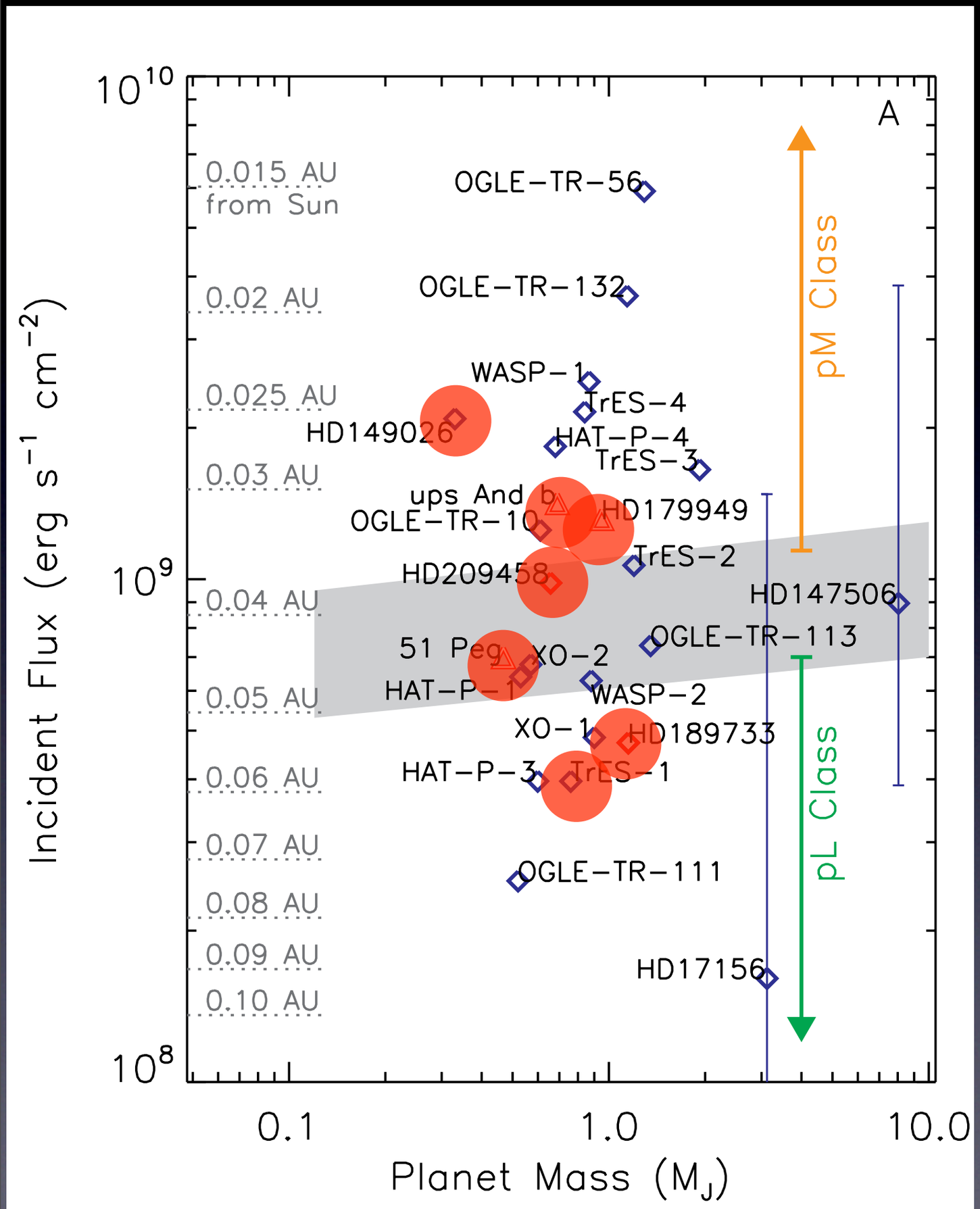
Fortney et al. (2008)



Fortney et al. (2007)

Tests

- pM class
  - large T_{brt}
  - emission features
  - high day/night contrast
  - TiO/VO bands
- pL class
  - low T_{brt}
  - absorption
  - low contrast
  - Na/K lines



Fortney et al. (2007)

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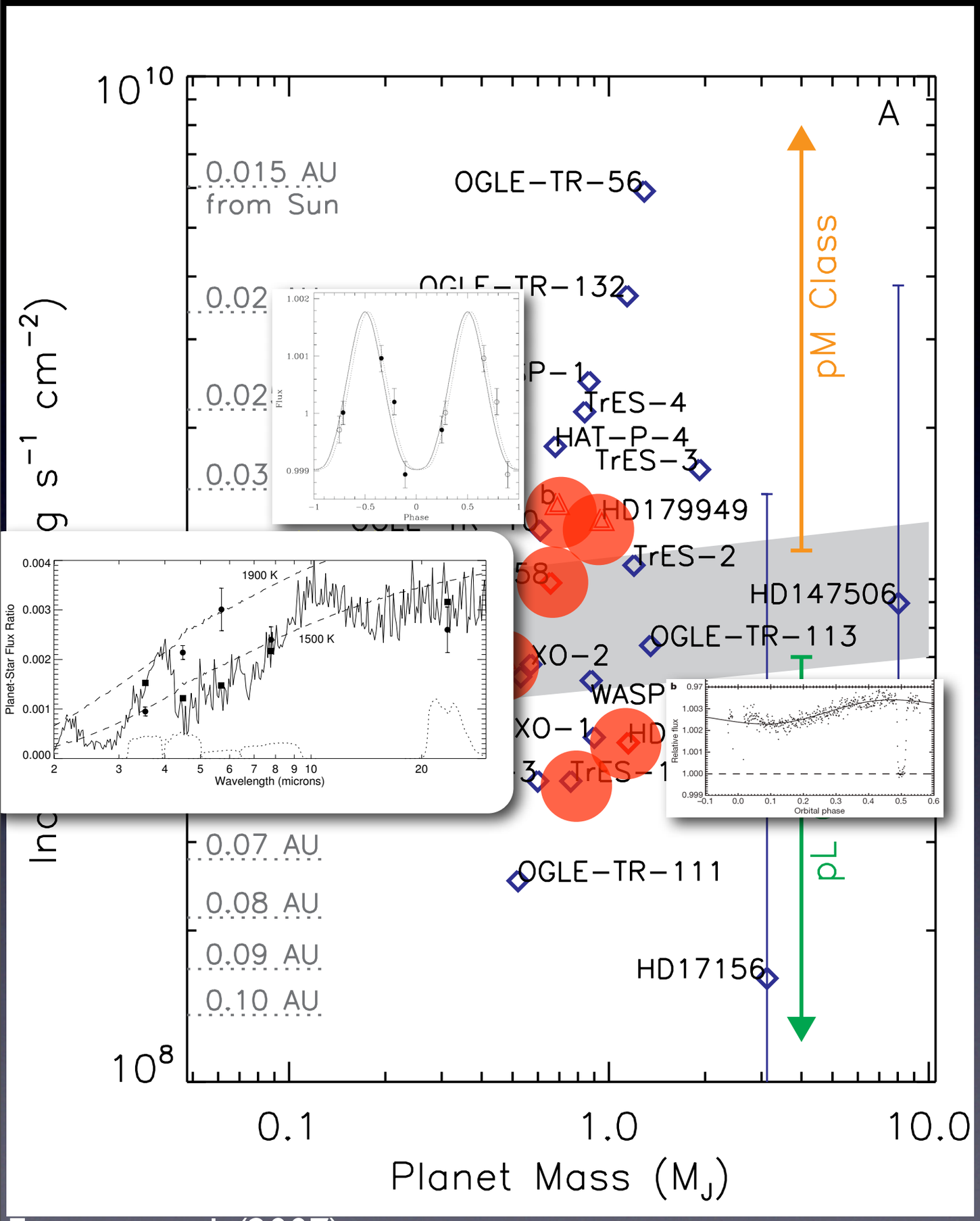
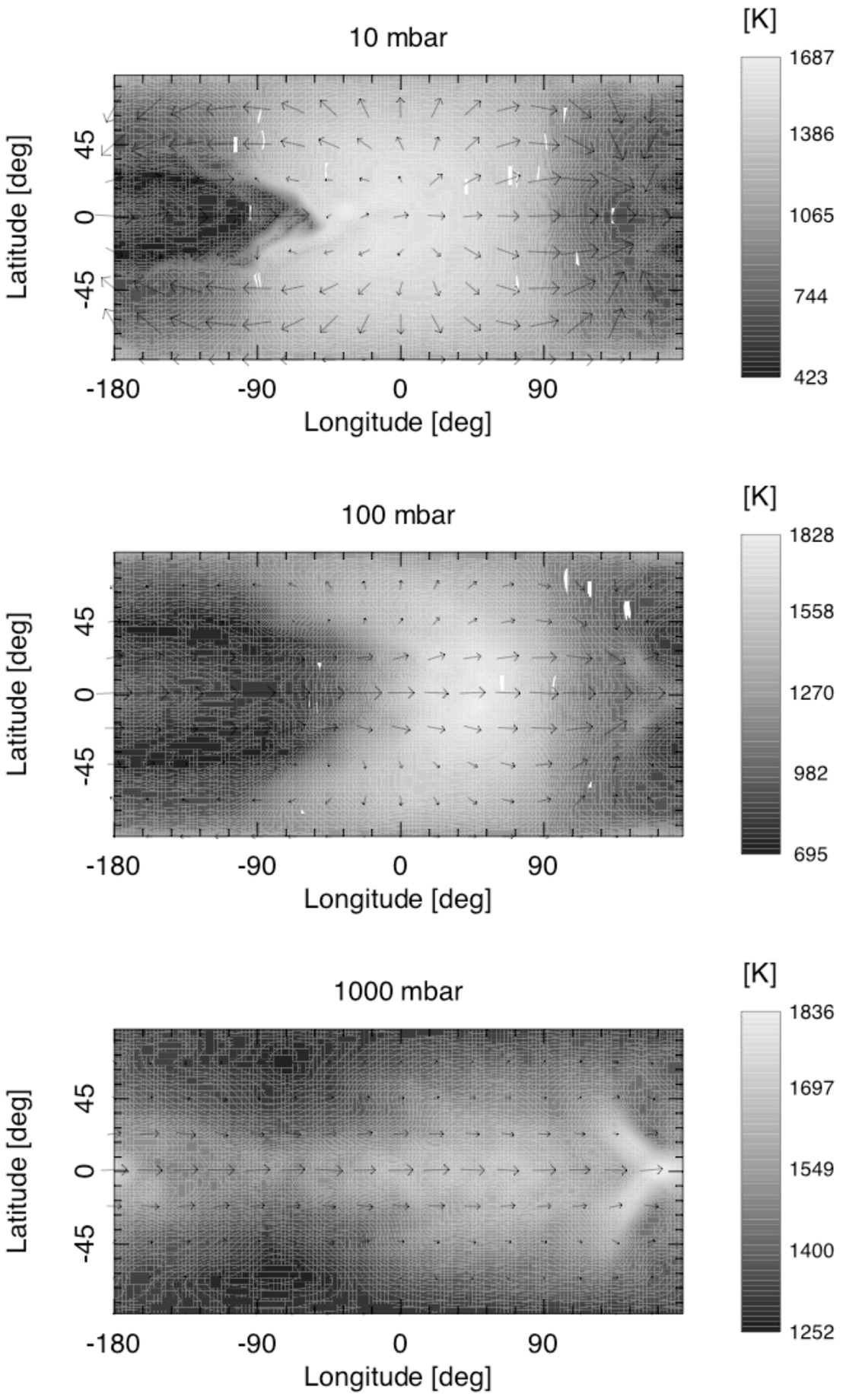


Fortney et al. (2007)

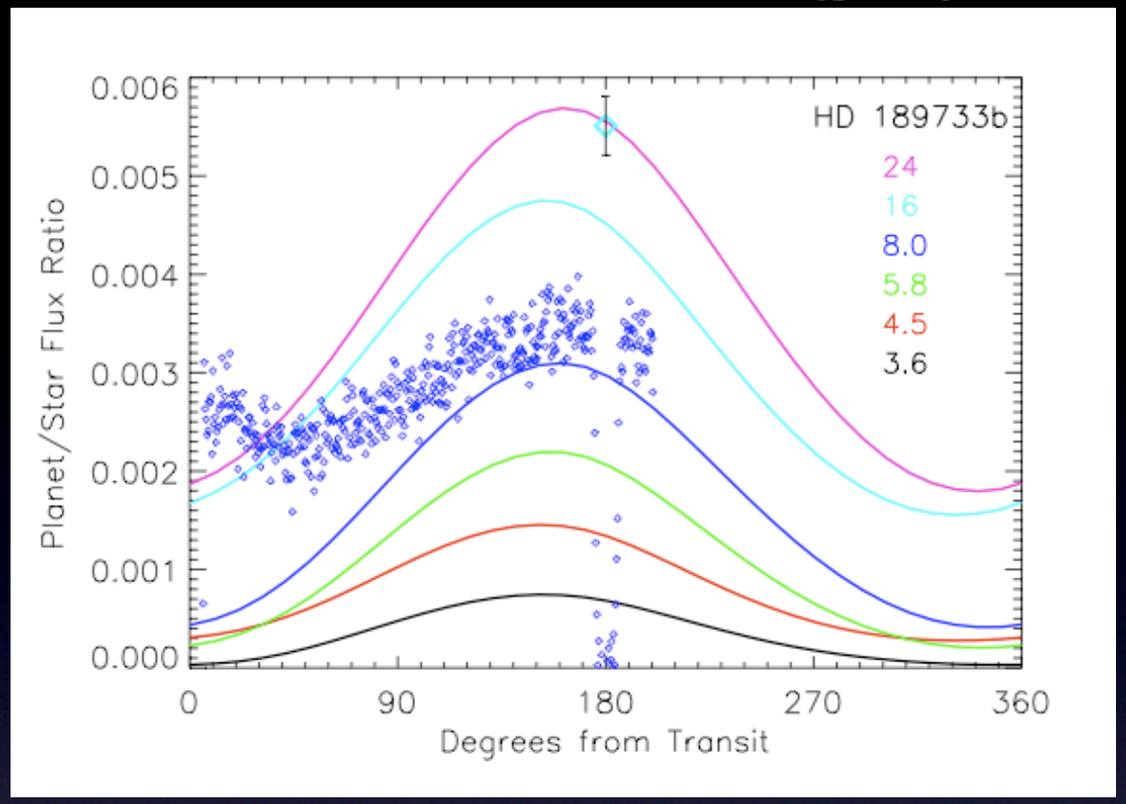
Tests

- pM class
  - large T_{brt}
  - emission features
  - high day/night contrast
  - TiO/VO bands
- pL class
  - low T_{brt}
  - absorption
  - low contrast
  - Na/K lines

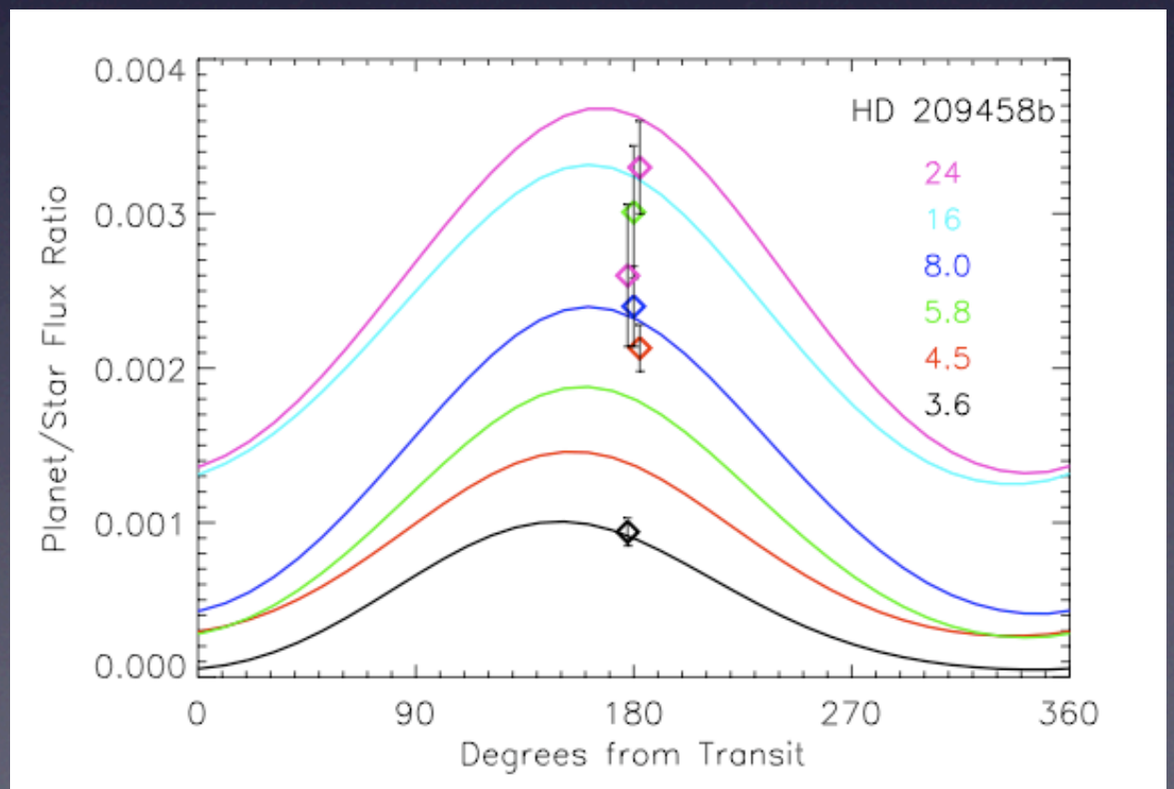


HD 189733b (pL)

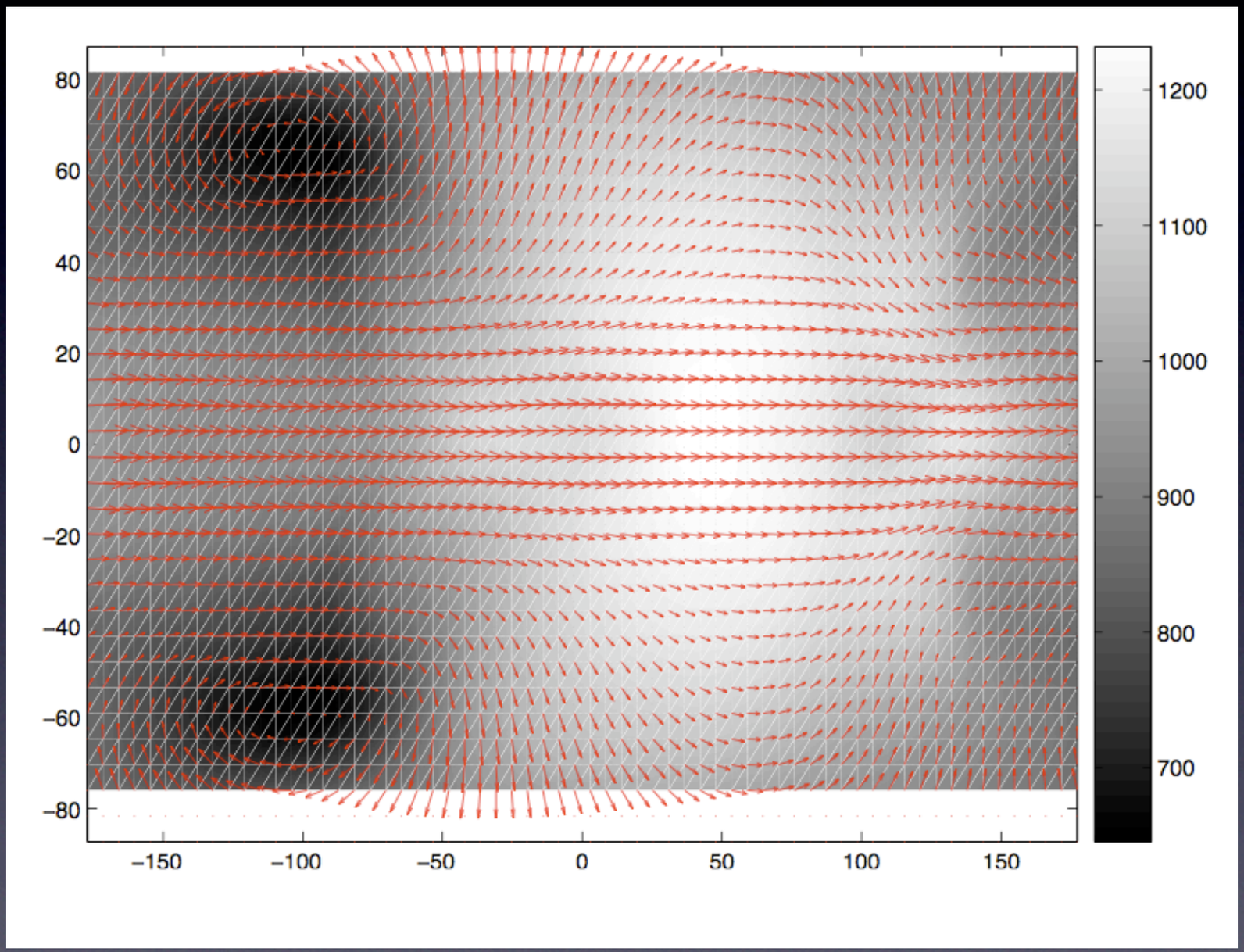
Showman et al. (2008)



HD 209458b (pM)



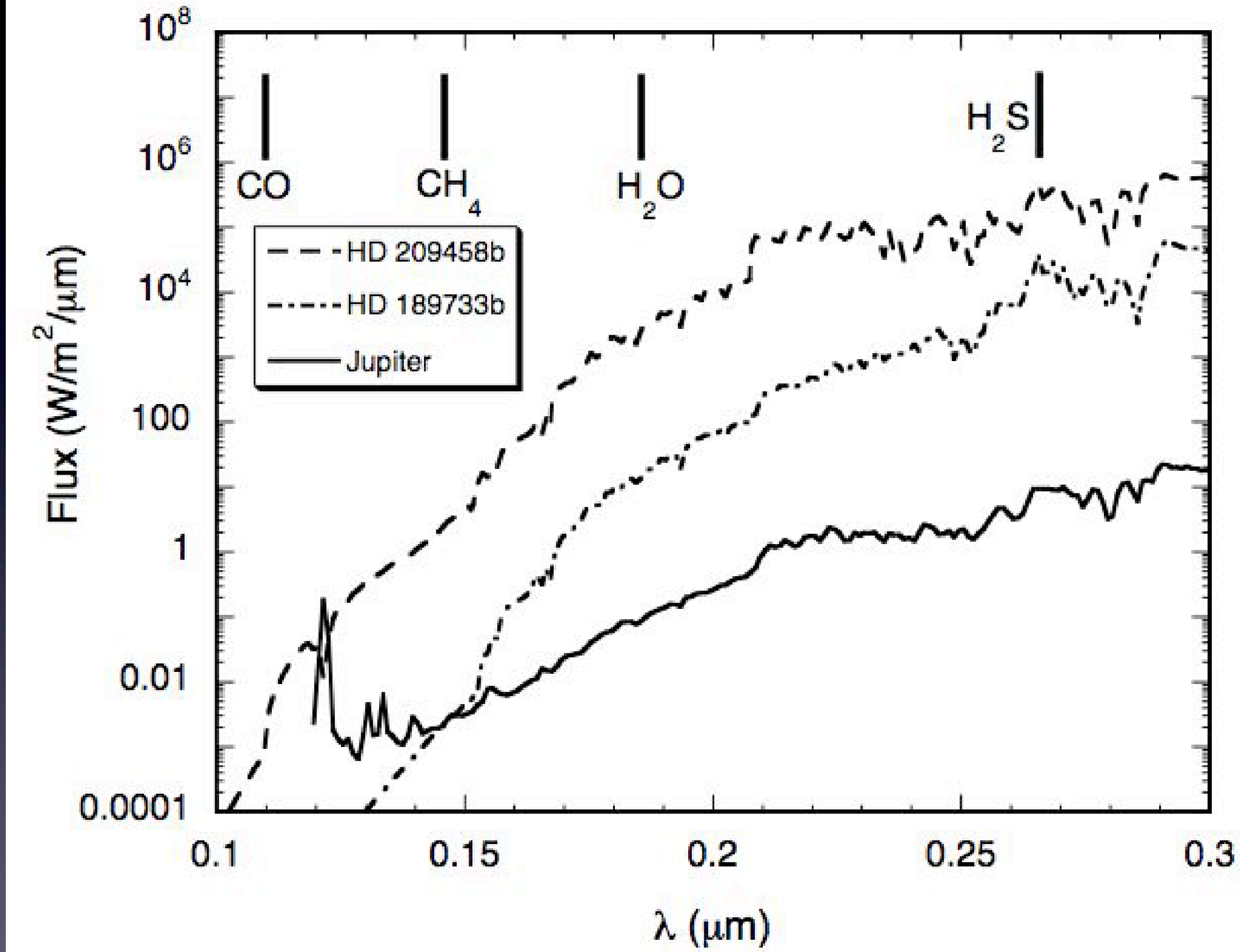
Need a GCM


80
60
40
20
0
−20
−40
−60
−80
−150
−100
−50
0
50
100
150
1200
1100
1000
900
800
700

Photochemistry

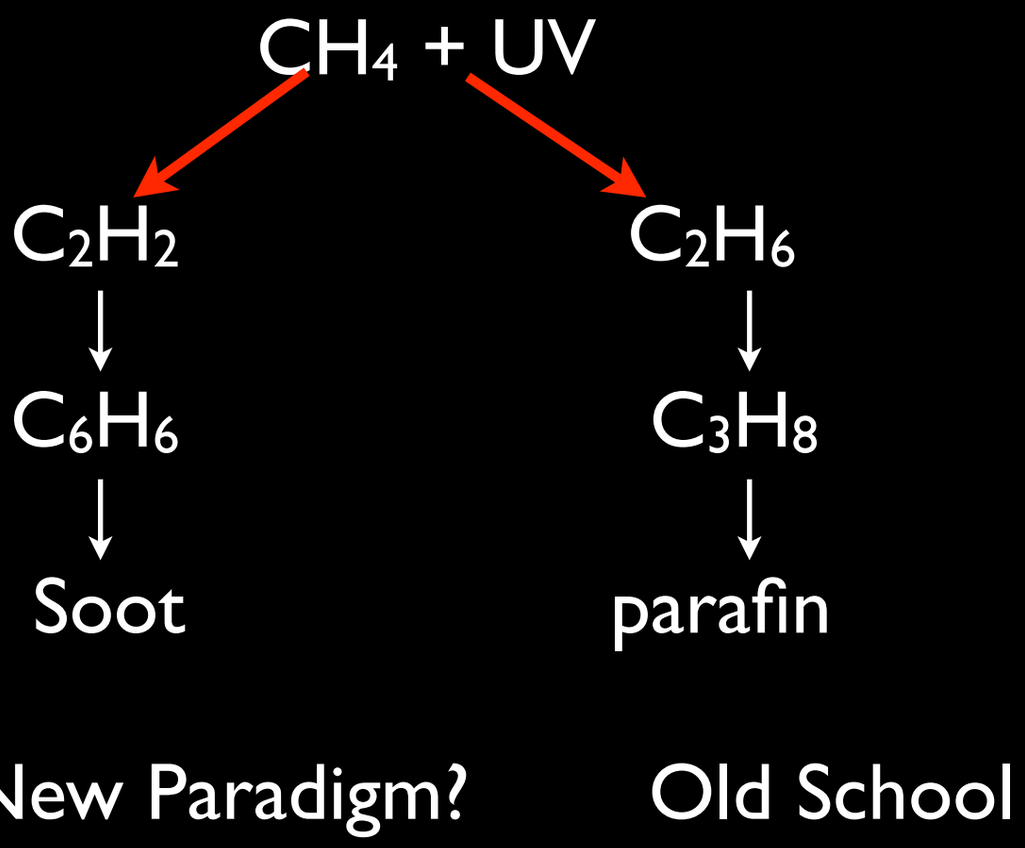
Jupiter at 1 AU

- 25x higher UV flux
- H, C, O, N, S, P chemistry
- Many pathways to hazes
- But...Liang et al. (2004) find no hazes in hot Jupiters



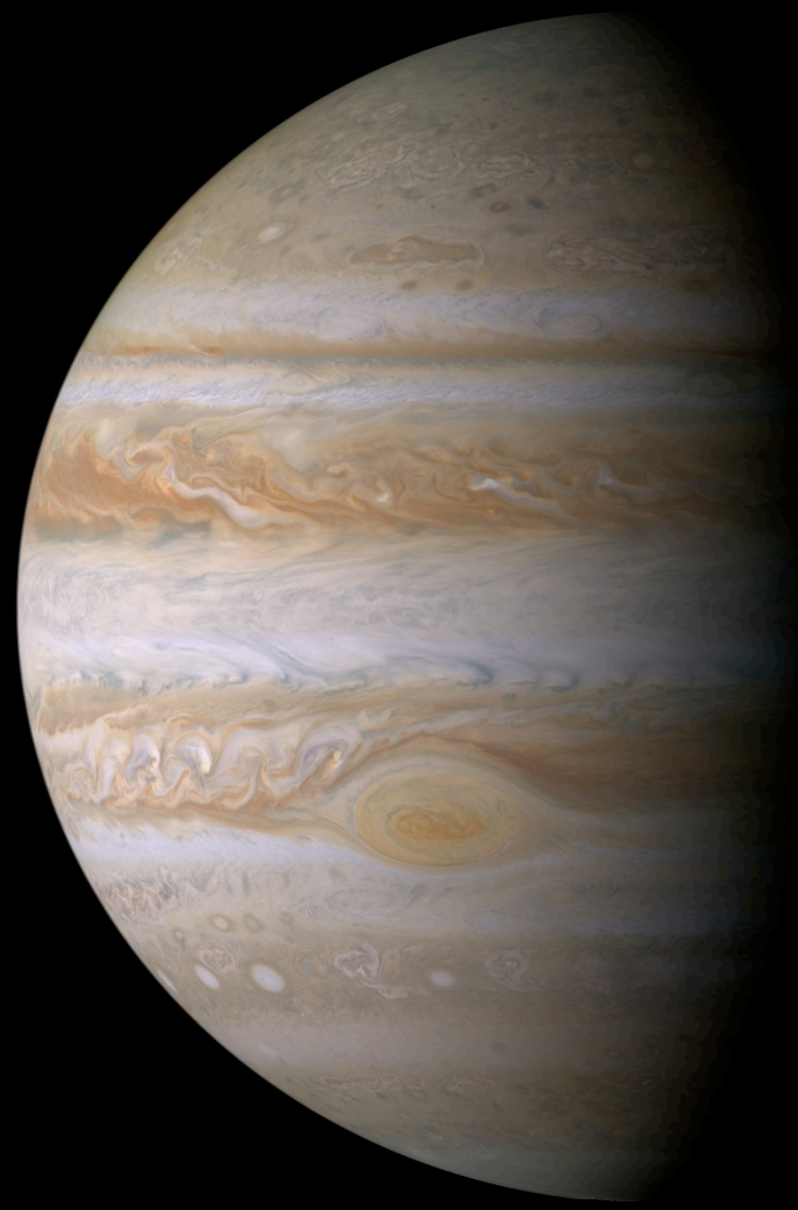
Marley et al. (2007)

Haze Production

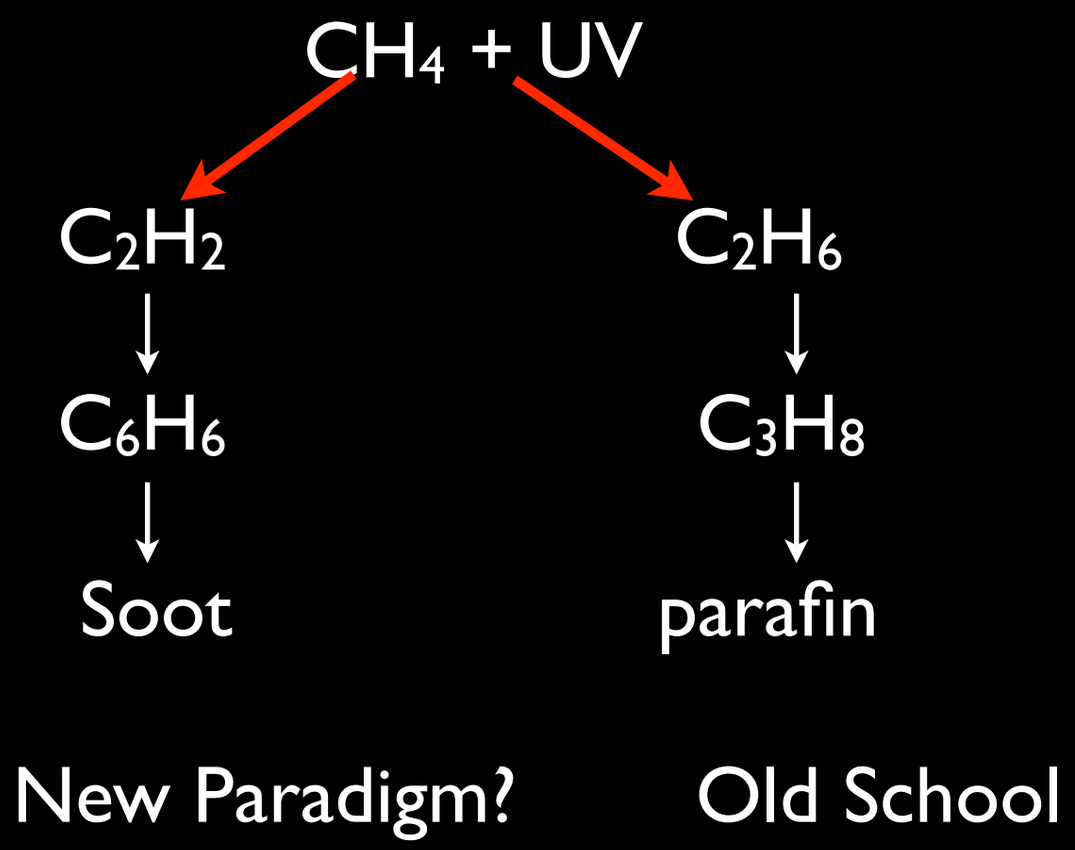


New Paradigm?

Old School



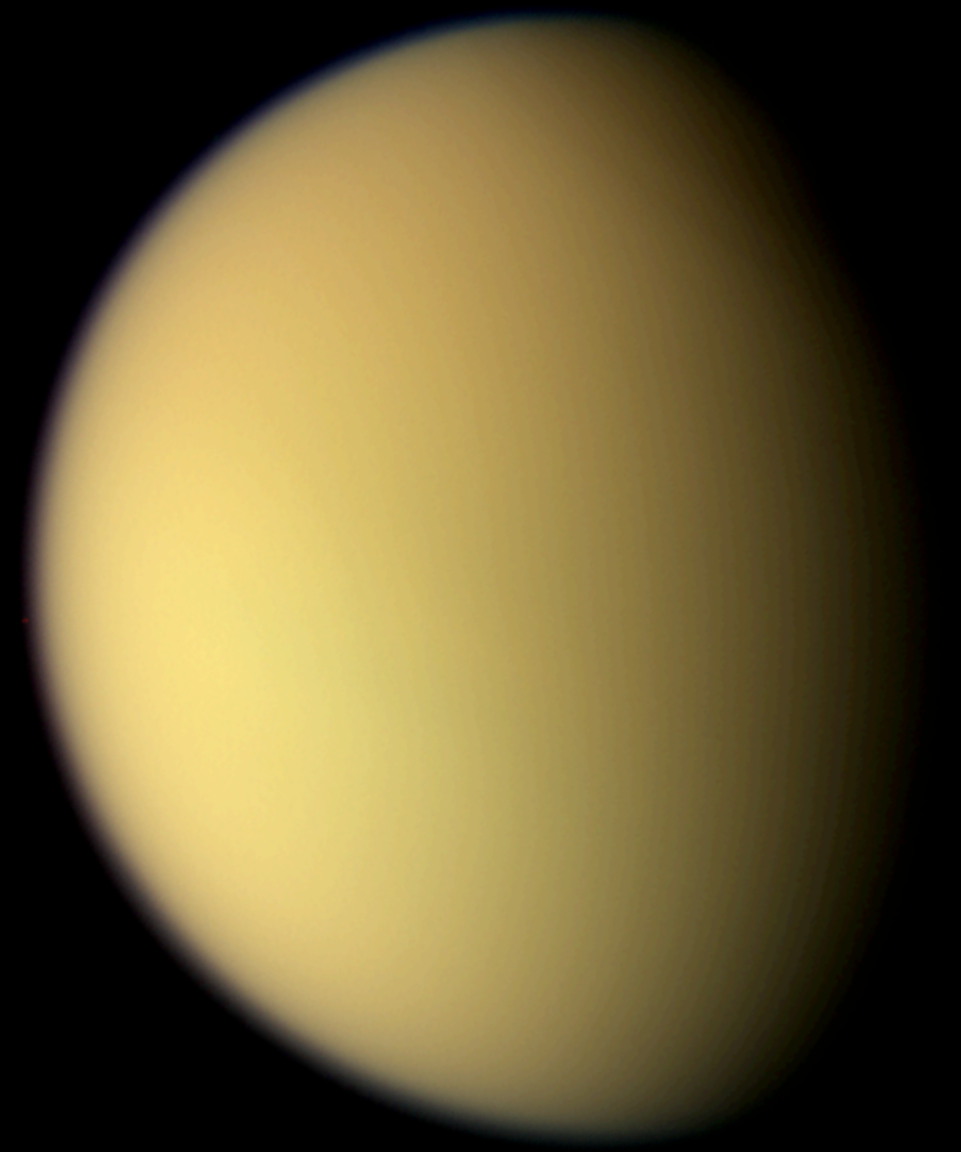
Haze Production



New Paradigm?

Old School

Substantially alter spectra and colors of canonical haze-free models



Alternative heating mechanism?

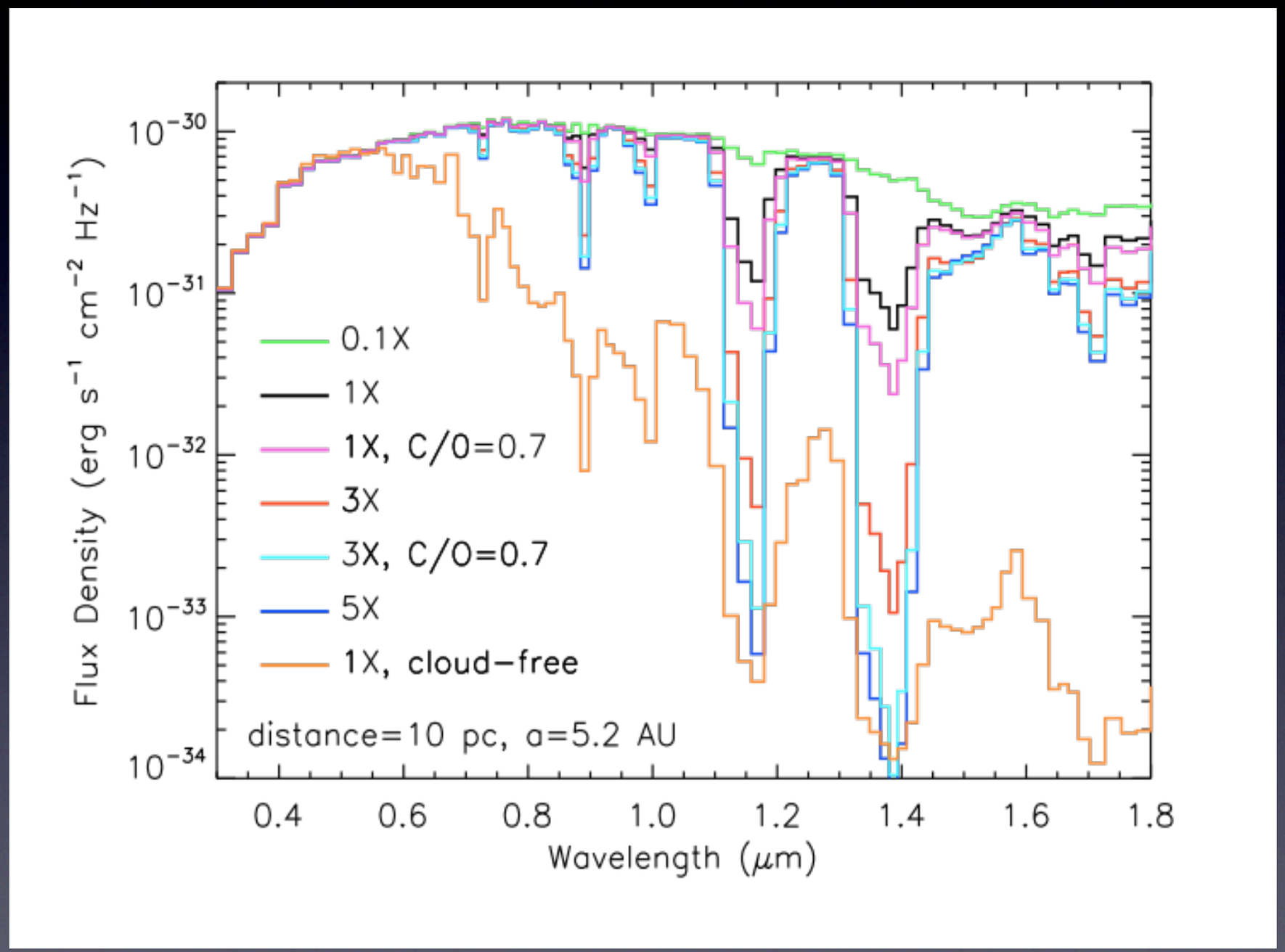
Clouds

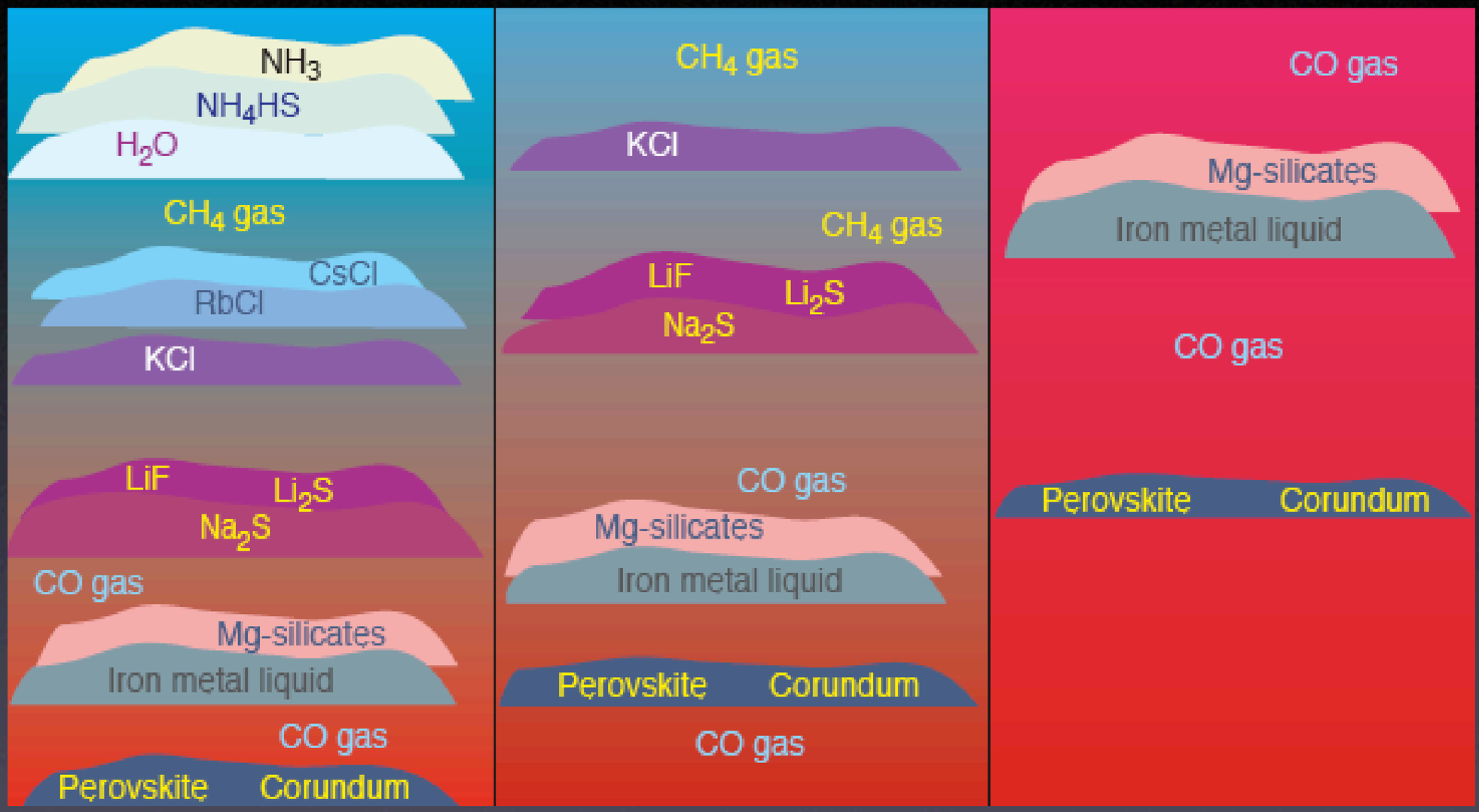
Characterization

- Mass - spectra
- Radius - spectra
- Albedo
- Effective temperature - spectra
  - Equilibrium temperature
  - Internal luminosity
- Atmospheric composition - spectra

Characterization Requires Spectra

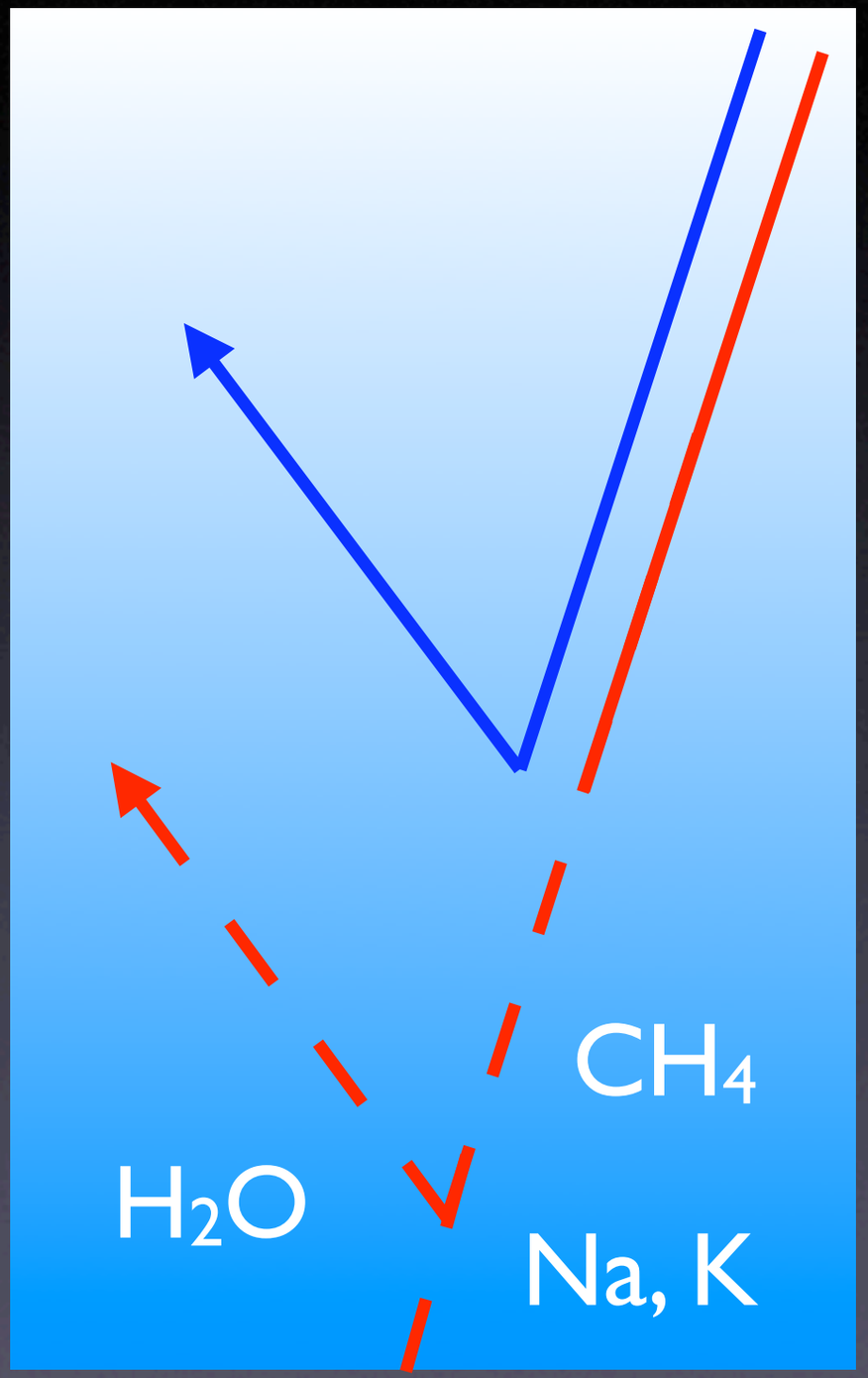
- band depths yield composition
- but likely contrast is too poor
- clouds control continuum
- but need a model for the clouds to extract interesting information

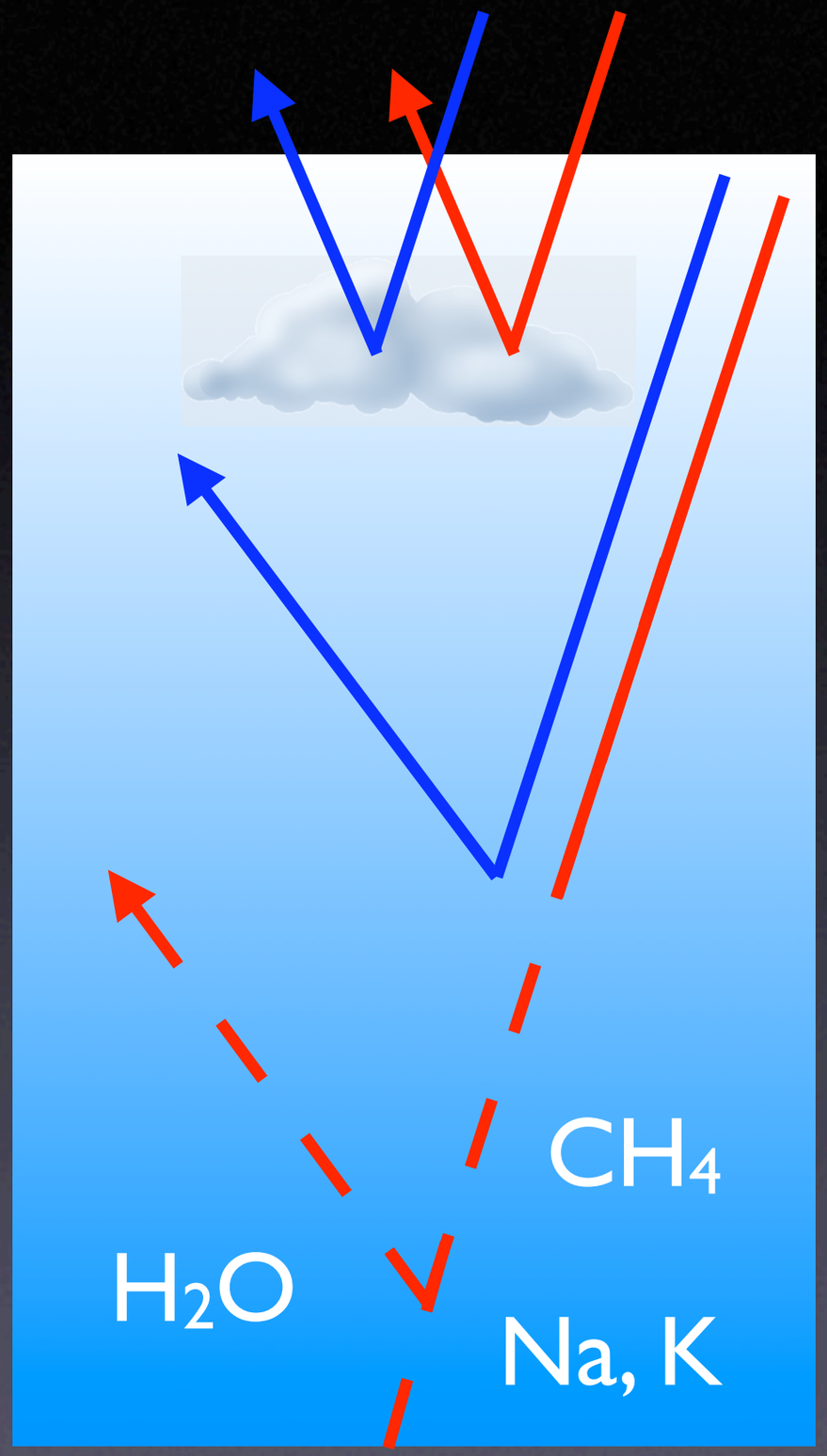


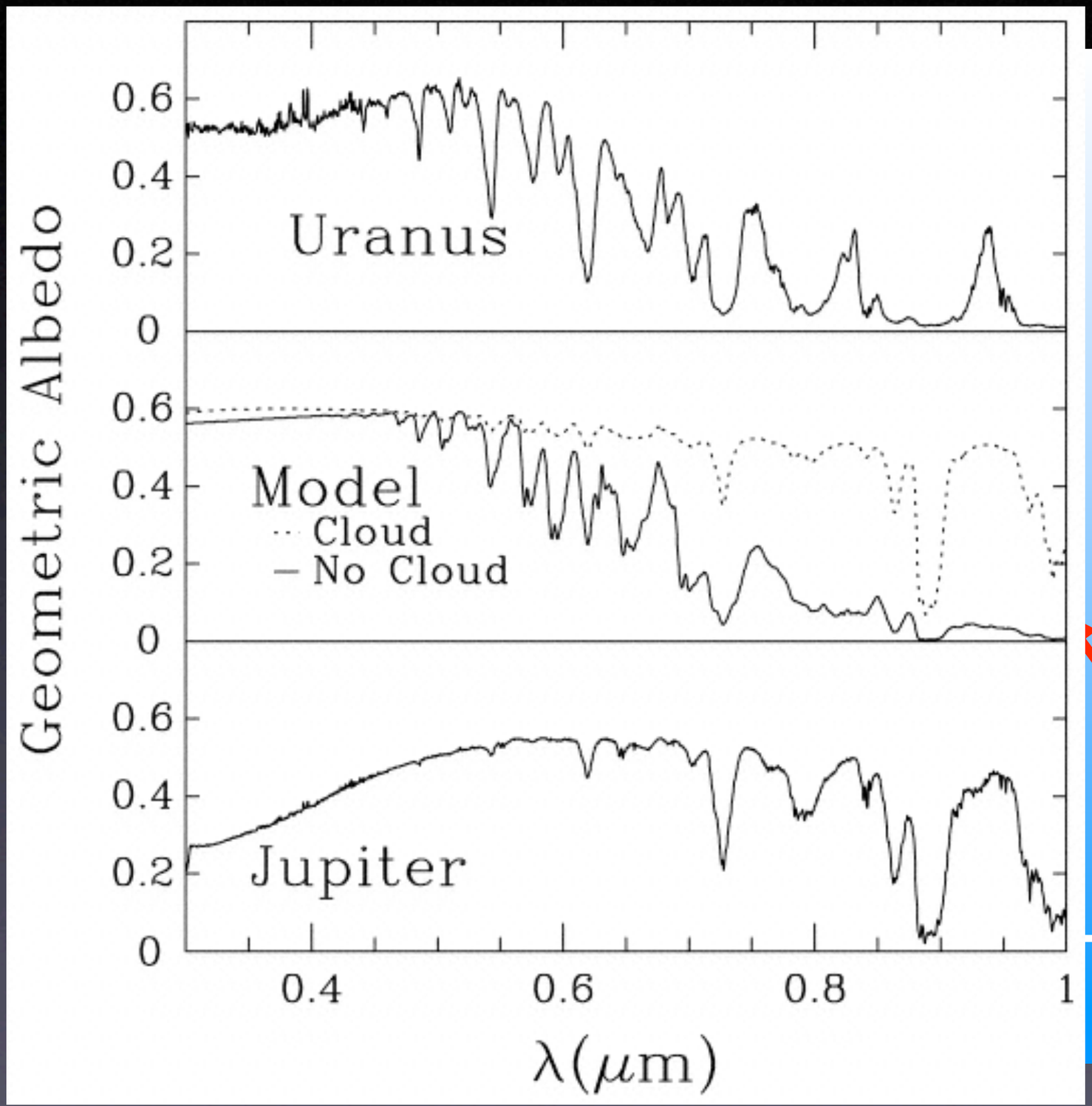


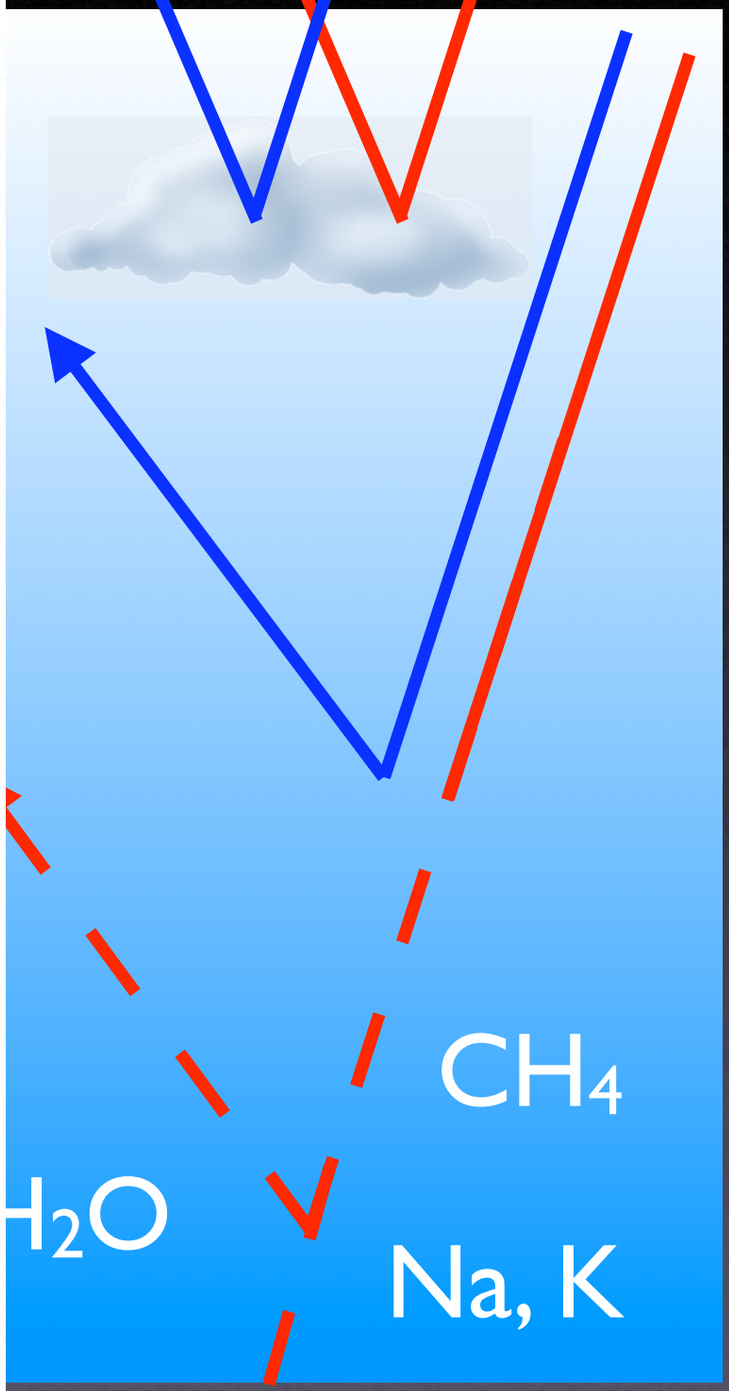
Jupiter Cloudless Hot Jupiter

Lodders (2005)


CH_4
H_2O
Na, K

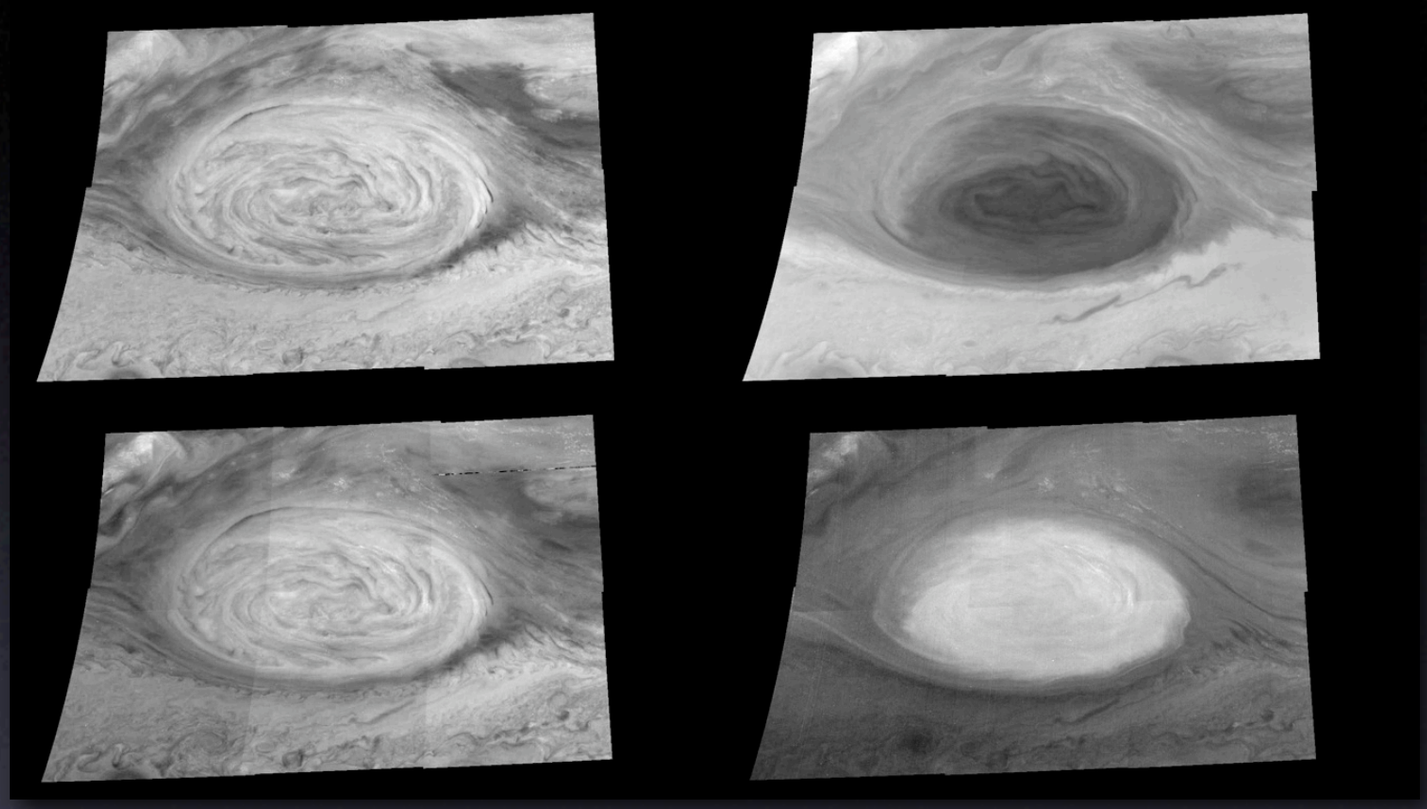

CH_4
H_2O
Na, K

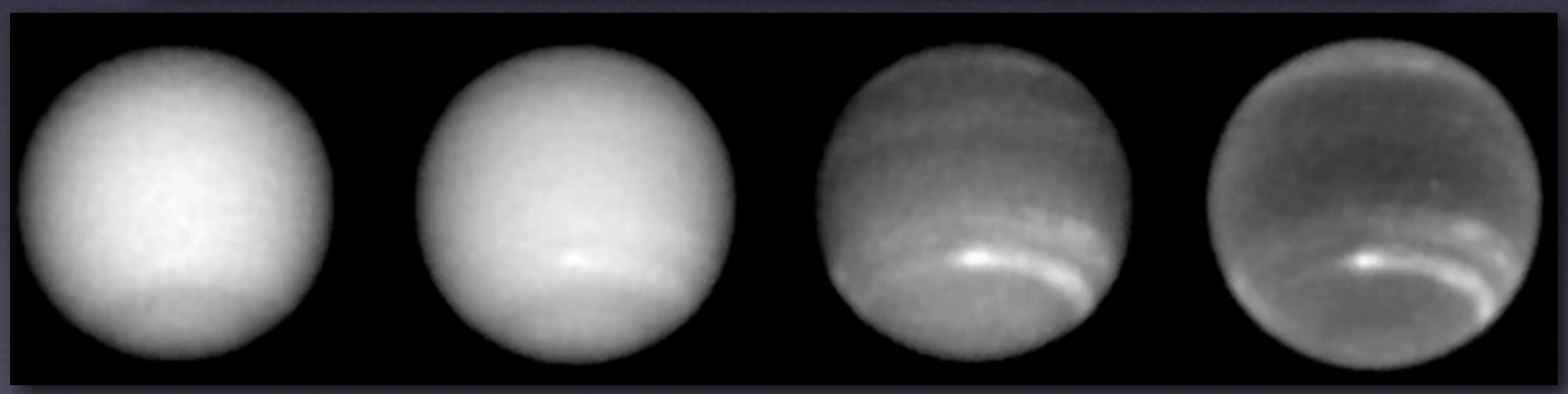




Marley et al. (1999)

Clouds are Challenging





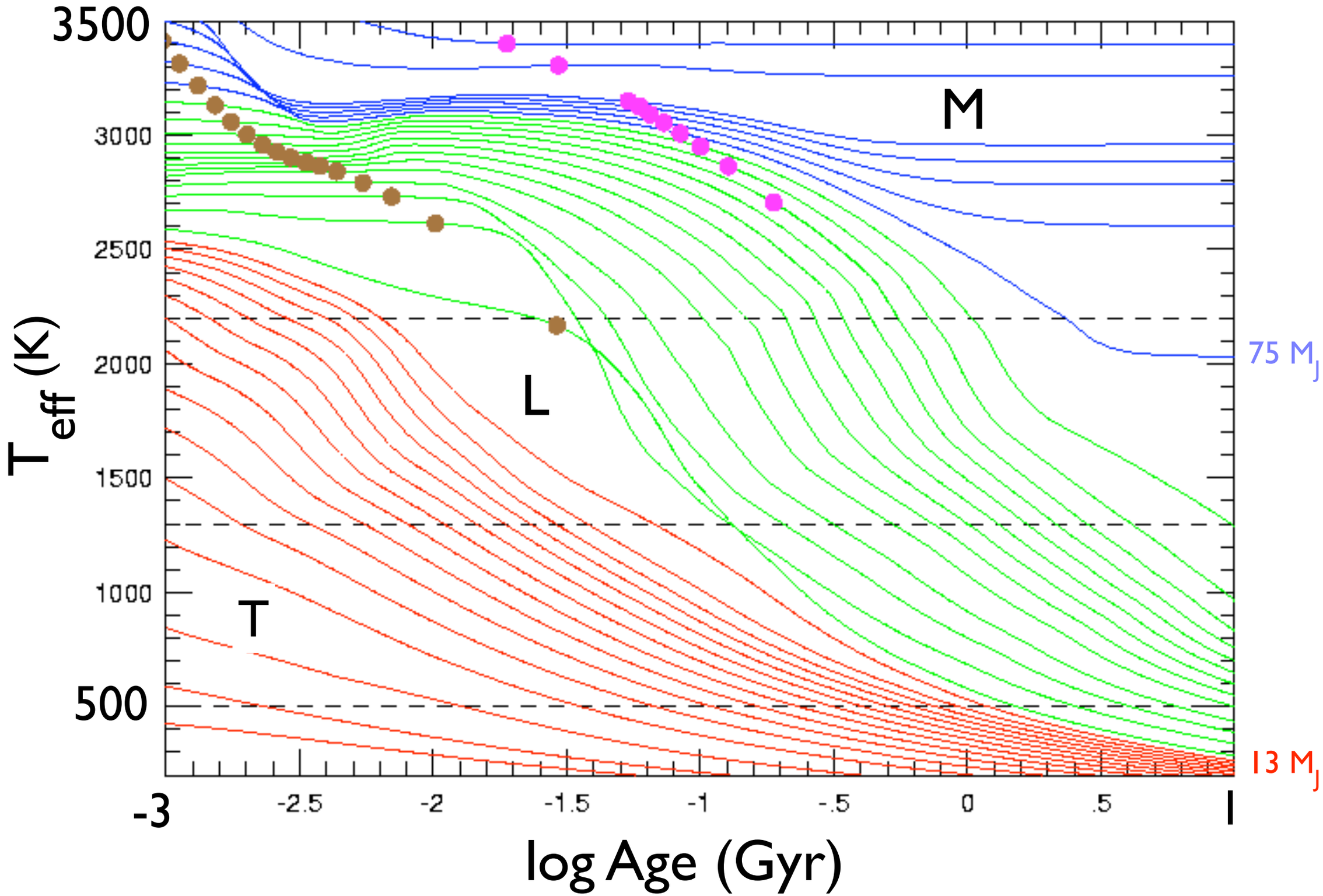
Clouds, aerosols, and photochemistry in the Jovian atmosphere

Robert A. WestDarrell F. StrobelMartin G. Tomasko

Top 10 most cited "Jupiter" paper

A Cautionary Tale

Brown Dwarfs



Burrows et al. 1997

DwarfArchives.org

Archives of photometry, spectroscopy, and parallaxes for all known L and T dwarfs.

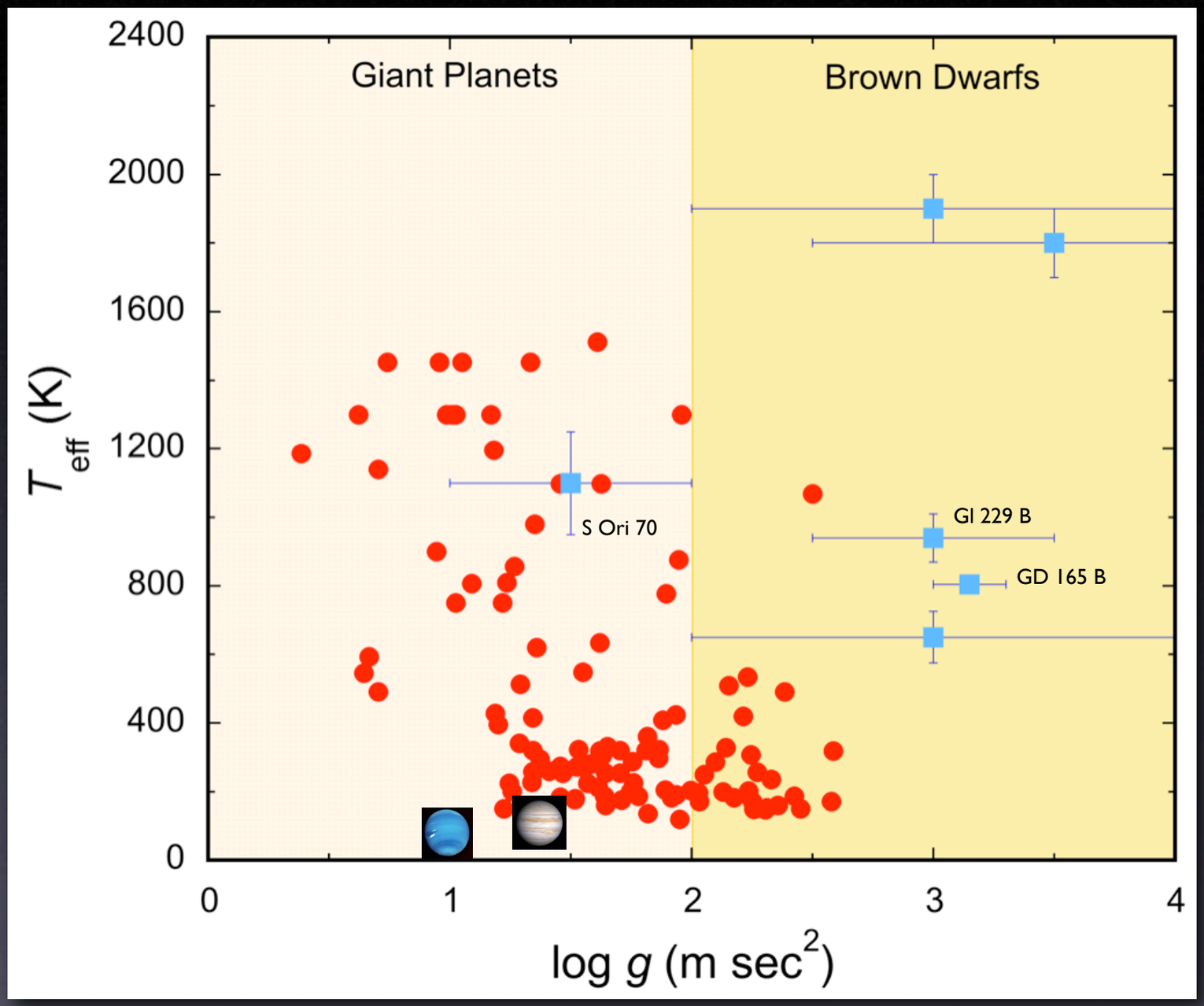
Archive search engine

Full list of 608 L and T dwarfs (html, text)
L dwarf-only list (html, text)
T dwarf-only list (html, text) - 122

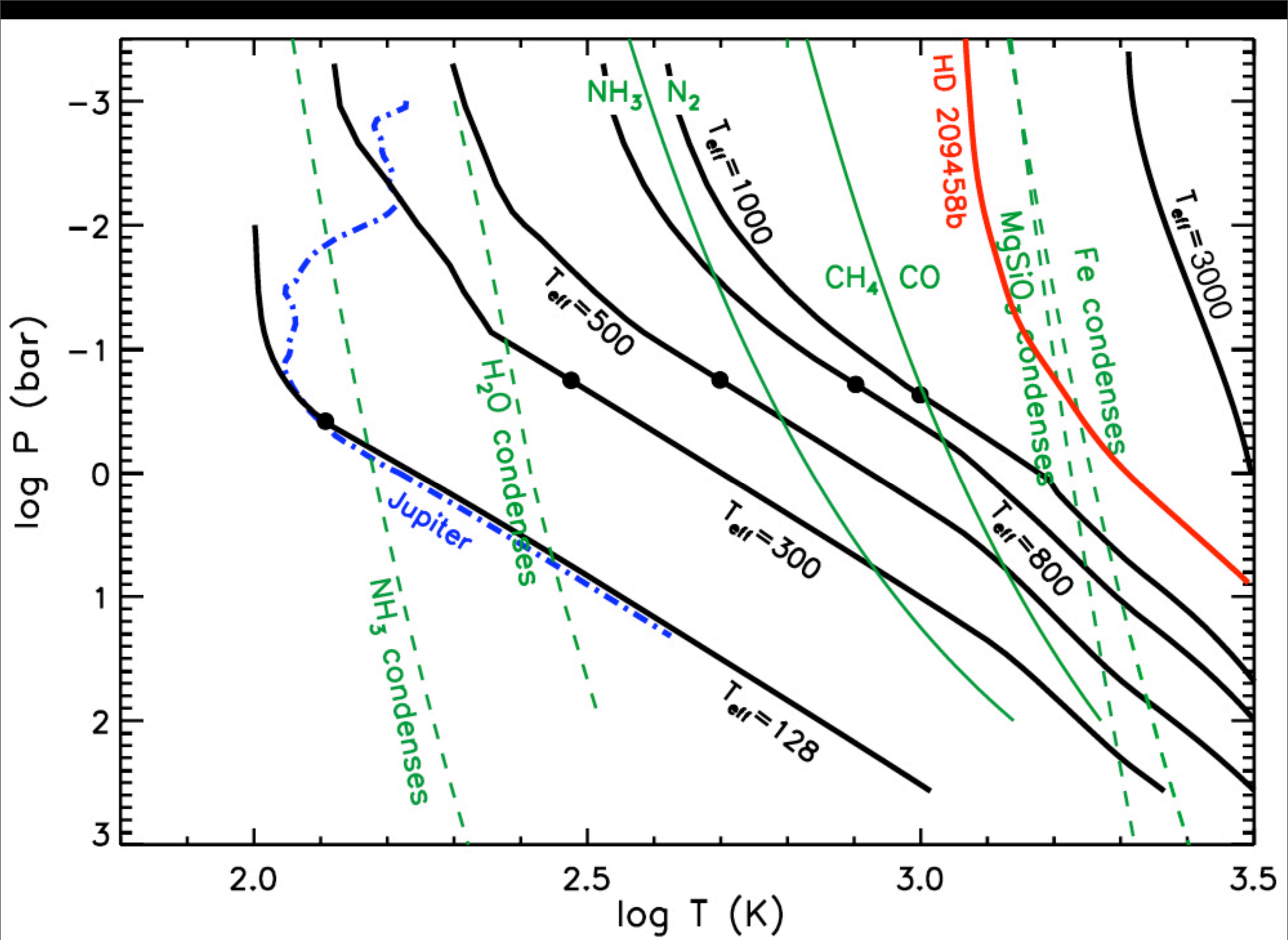
Spectra

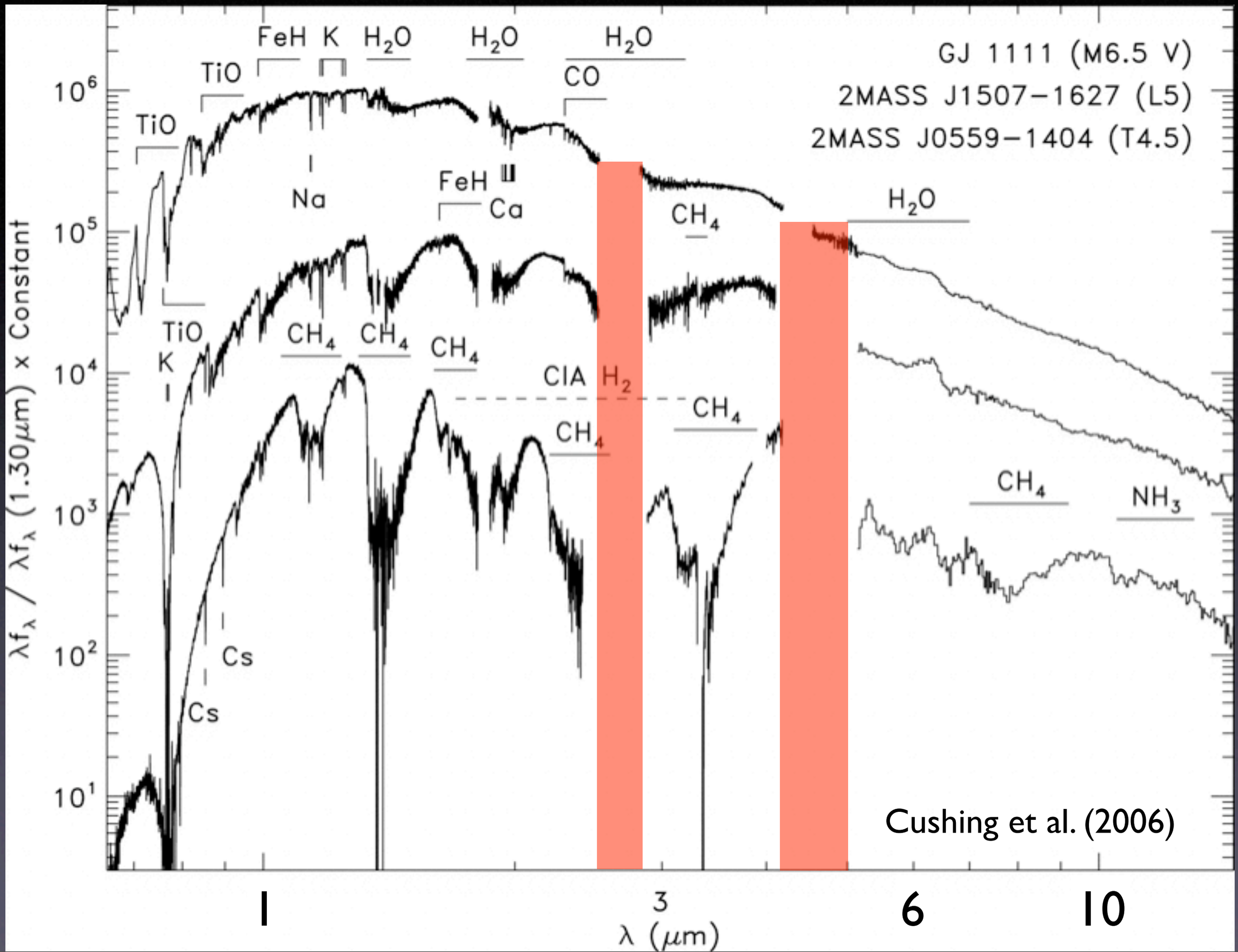
Measured parallaxes (html, text) - 77

Planet & BD Discoveries

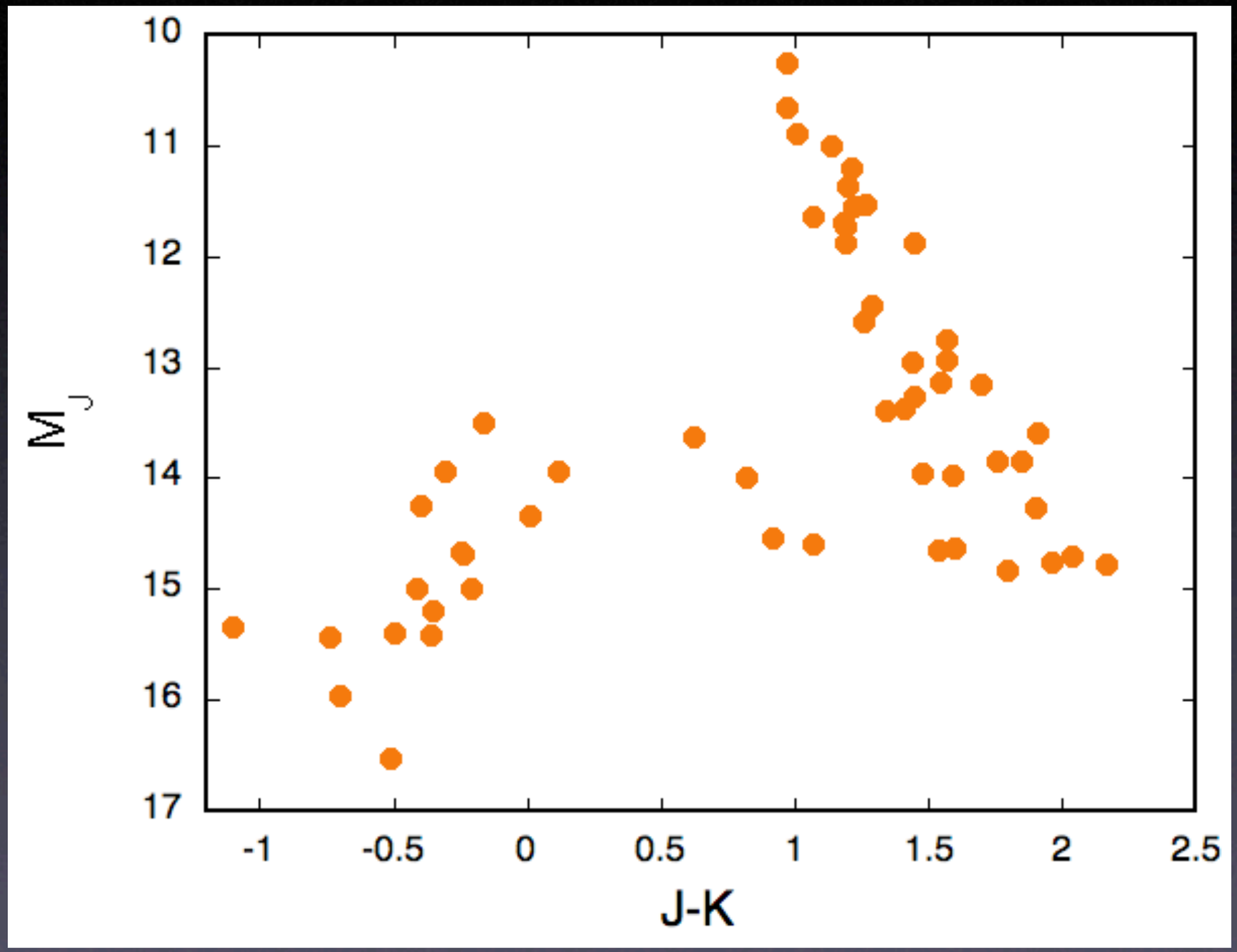


- T_{eff} of known BDs span much of the EGP discovery space
- g influence on emergent spectra tends to be small (note large g error bars)
- Planet/BD distinction is already blurry


HD 209458b
MgSiO3 condenses
Fe condenses
NH3
N2
CH4
CO
H2O condenses
NH3 condenses
Jupiter
Teff=3000
Teff=1000
Teff=500
Teff=300
Teff=800
Teff=128
log P (bar)
log T (K)
−3
−2
−1
0
1
2
3
2.0
2.5
3.0
3.5

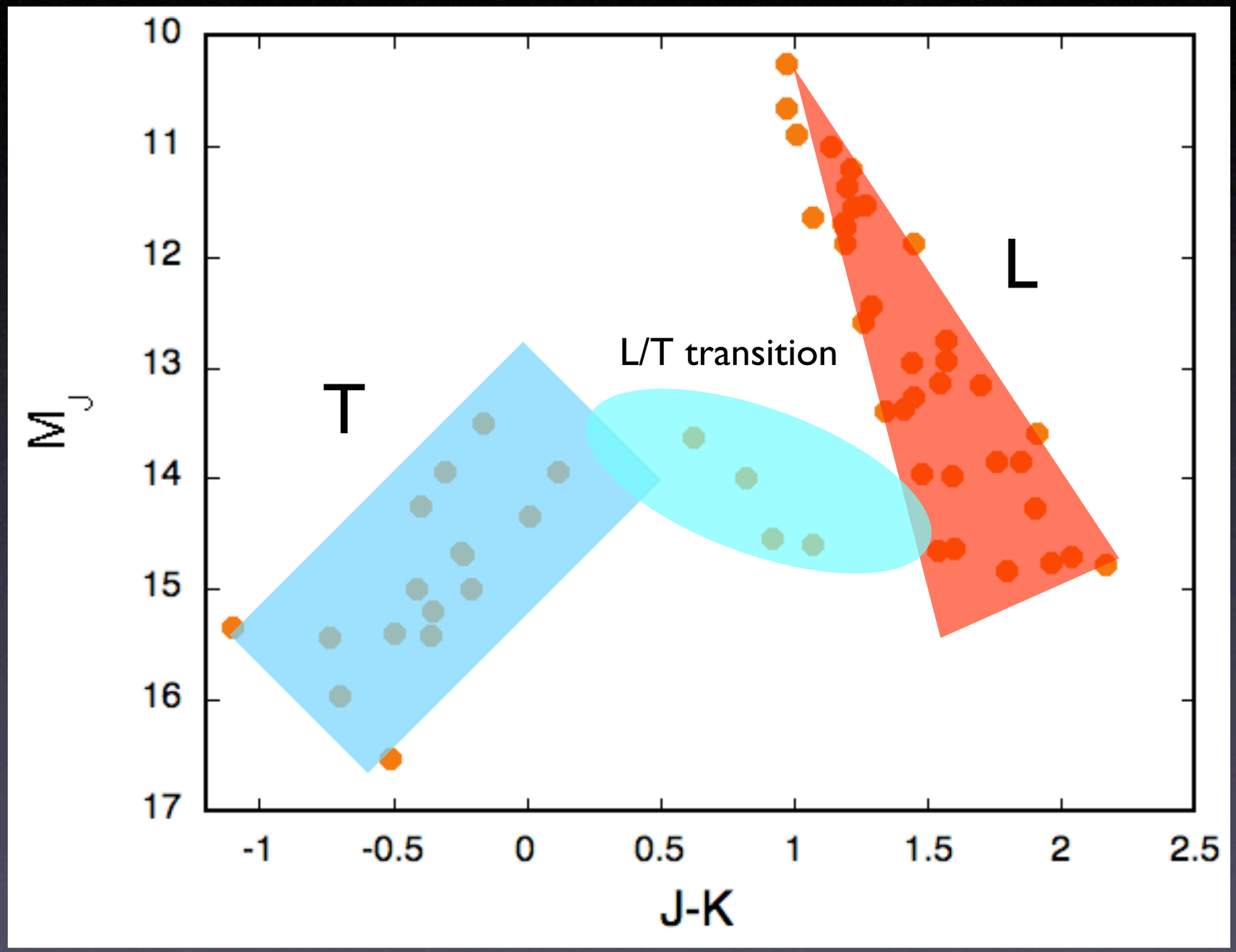

GJ 1111 (M6.5 V)
2MASS J1507−1627 (L5)
2MASS J0559−1404 (T4.5)
FeH
K
H2O
H2O
H2O
TiO
CO
TiO
Na
FeH
Ca
CH4
H2O
TiO
K
CH4
CH4
CH4
CIA
H2
CH4
CH4
CH4
NH3
Cs
Cs
λfλ / λfλ (1.30μm) x Constant
10^6
10^5
10^4
10^3
10^2
10^1
1
3
6
10
λ (μm)
Cushing et al. (2006)

Colors



- L's become progressively redder, with some scatter
- Rapid transition in J-K color to T dwarfs
- Early T's are brighter than late L's at J band

Colors



- L's become progressively redder, with some scatter
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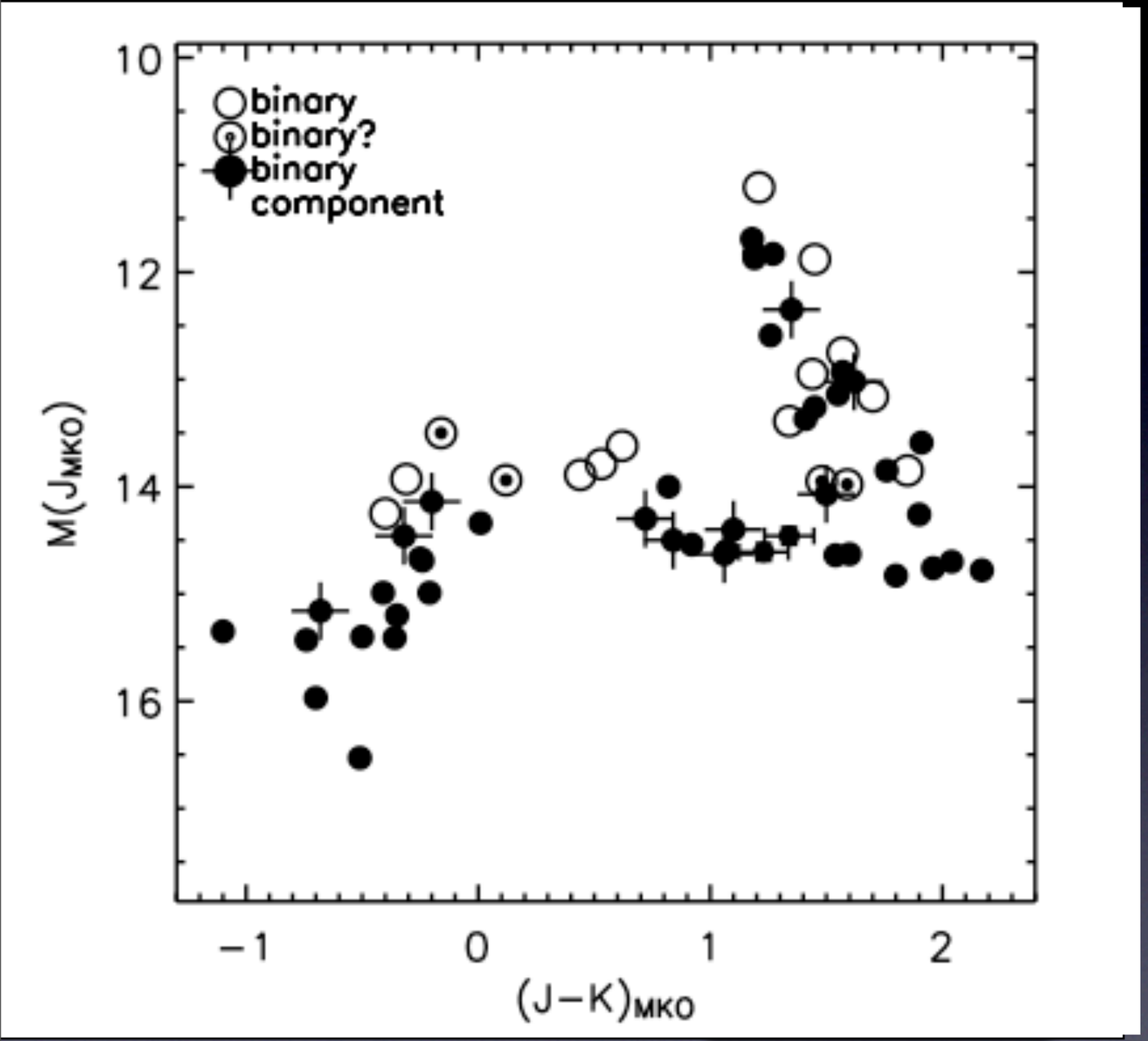
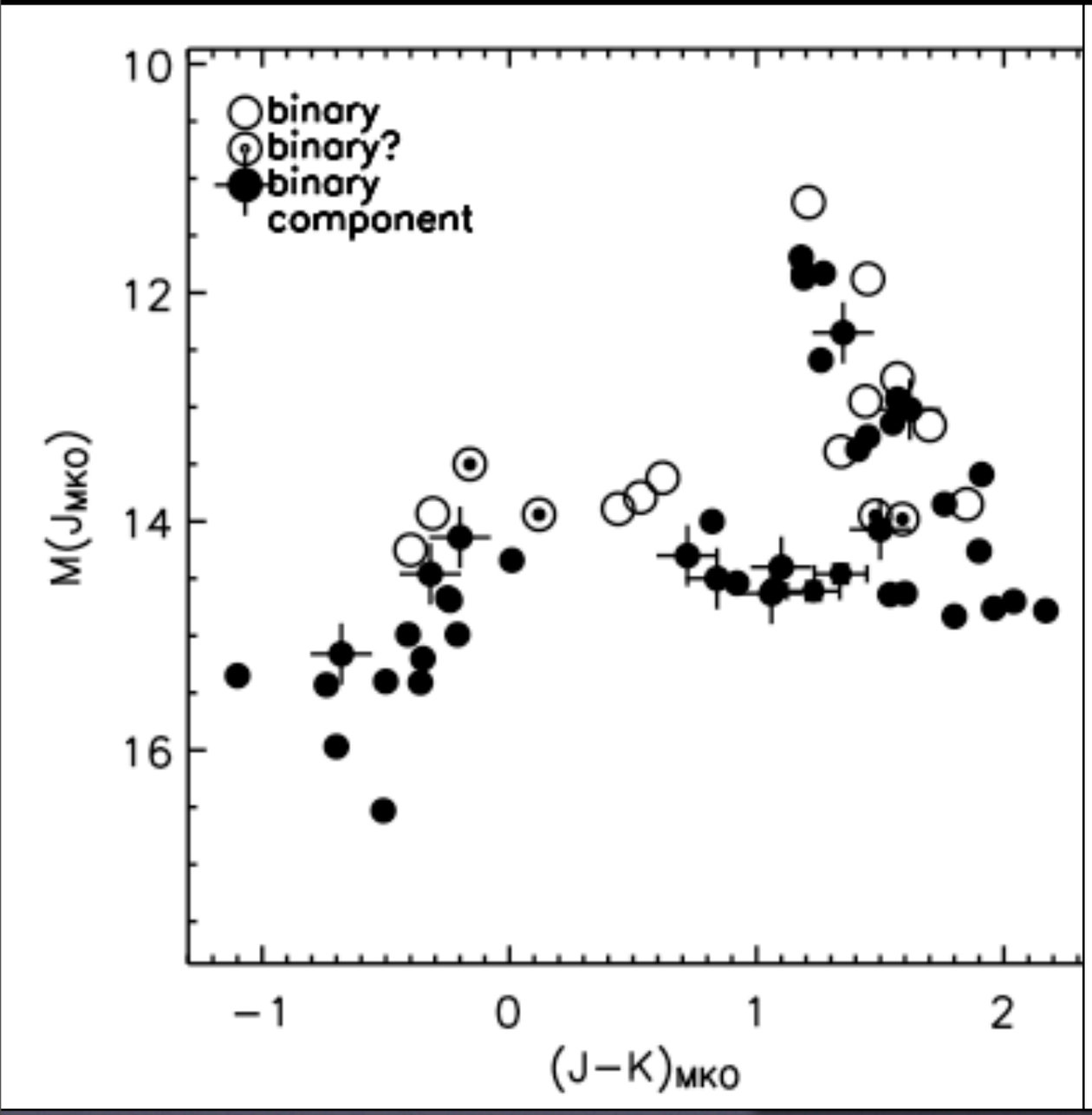
- Early T's are brighter than late L's at J band

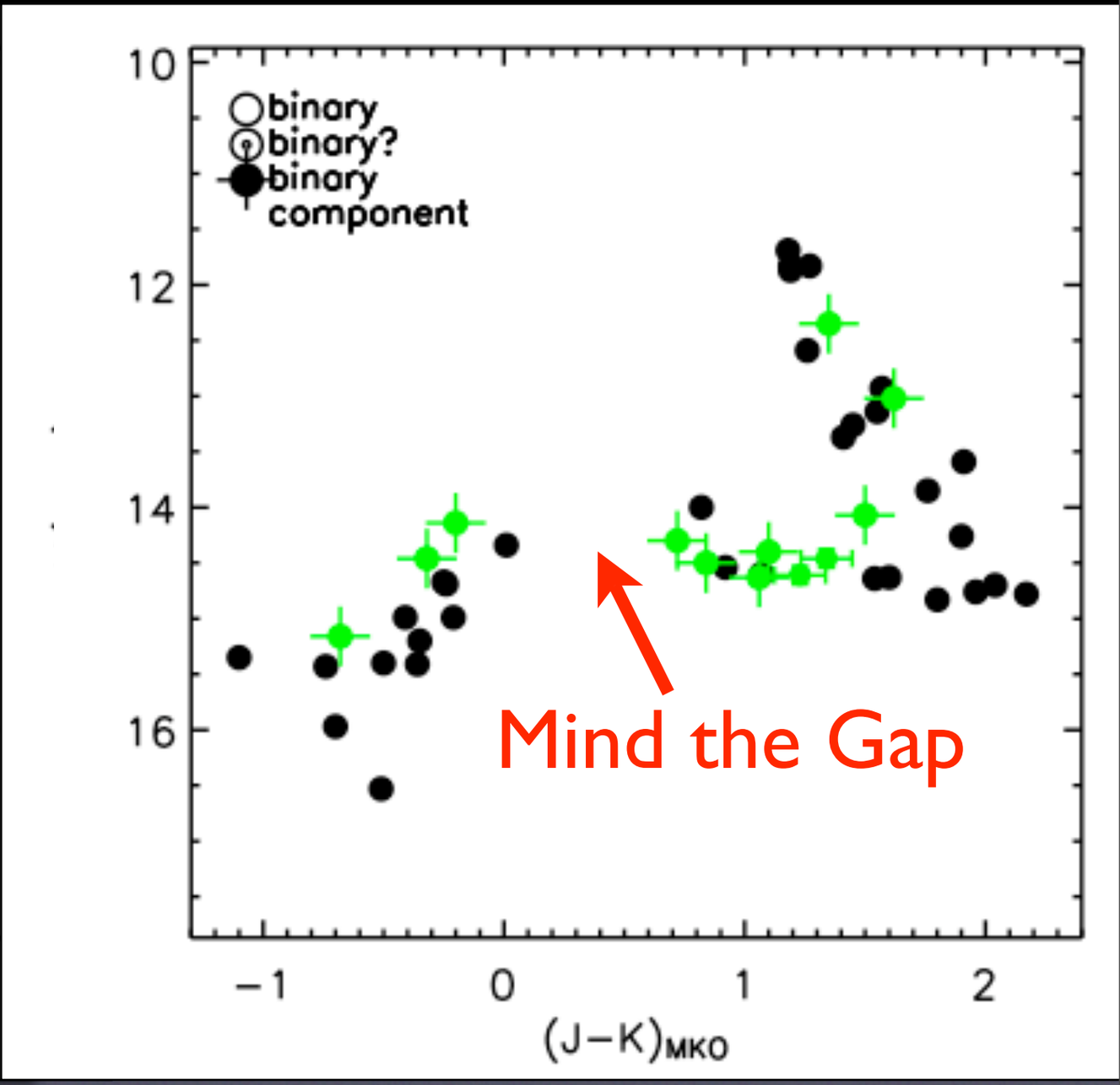
Transition is Rapid



Liu et al. (2007)

Transition is Rapid

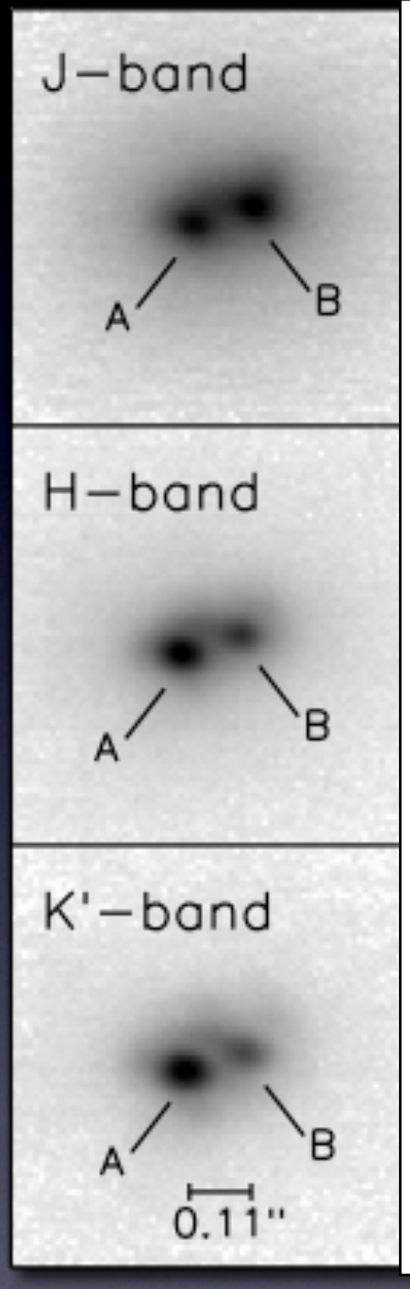


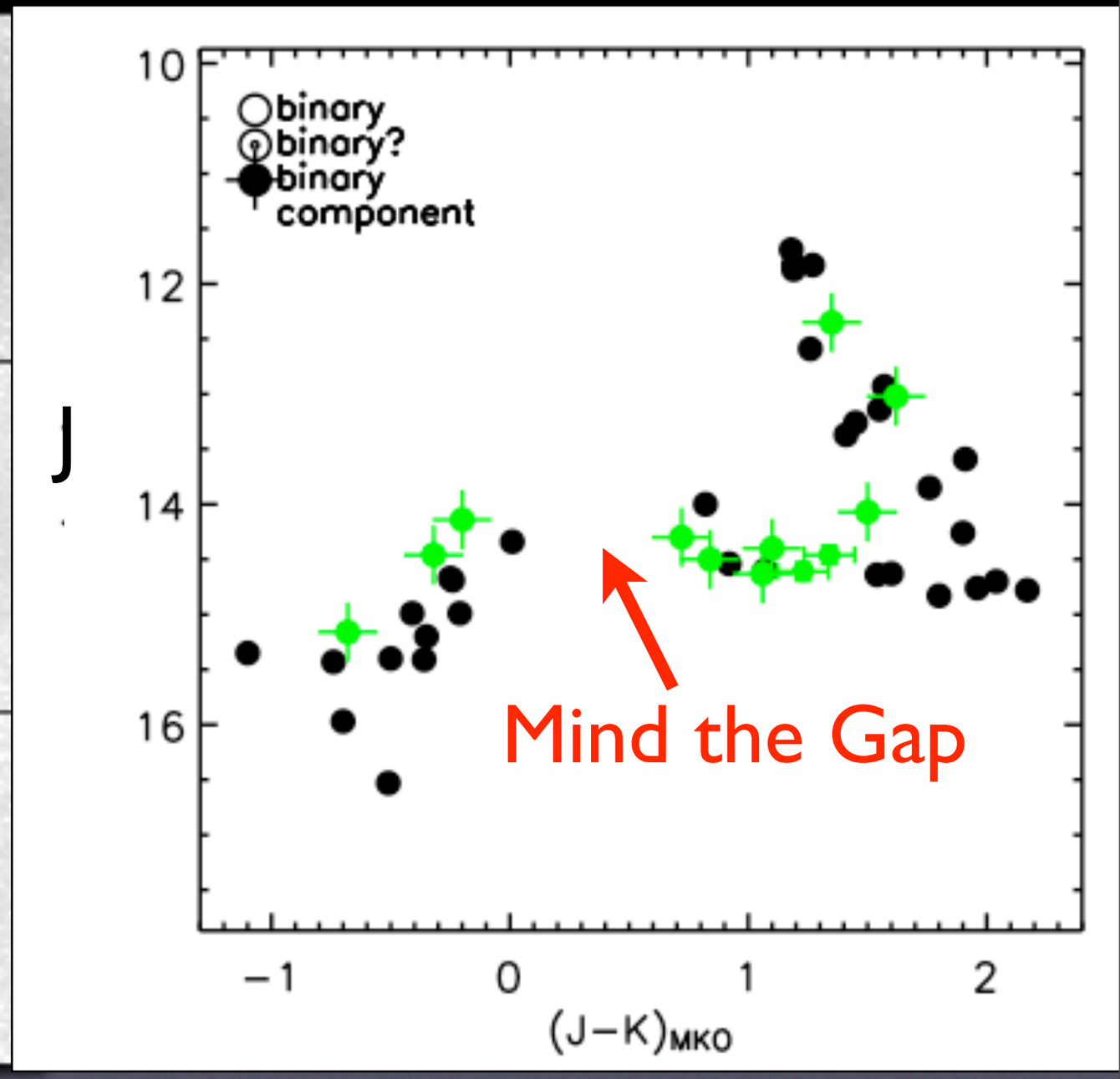


Liu et al. (2007)

Transition is Rapid

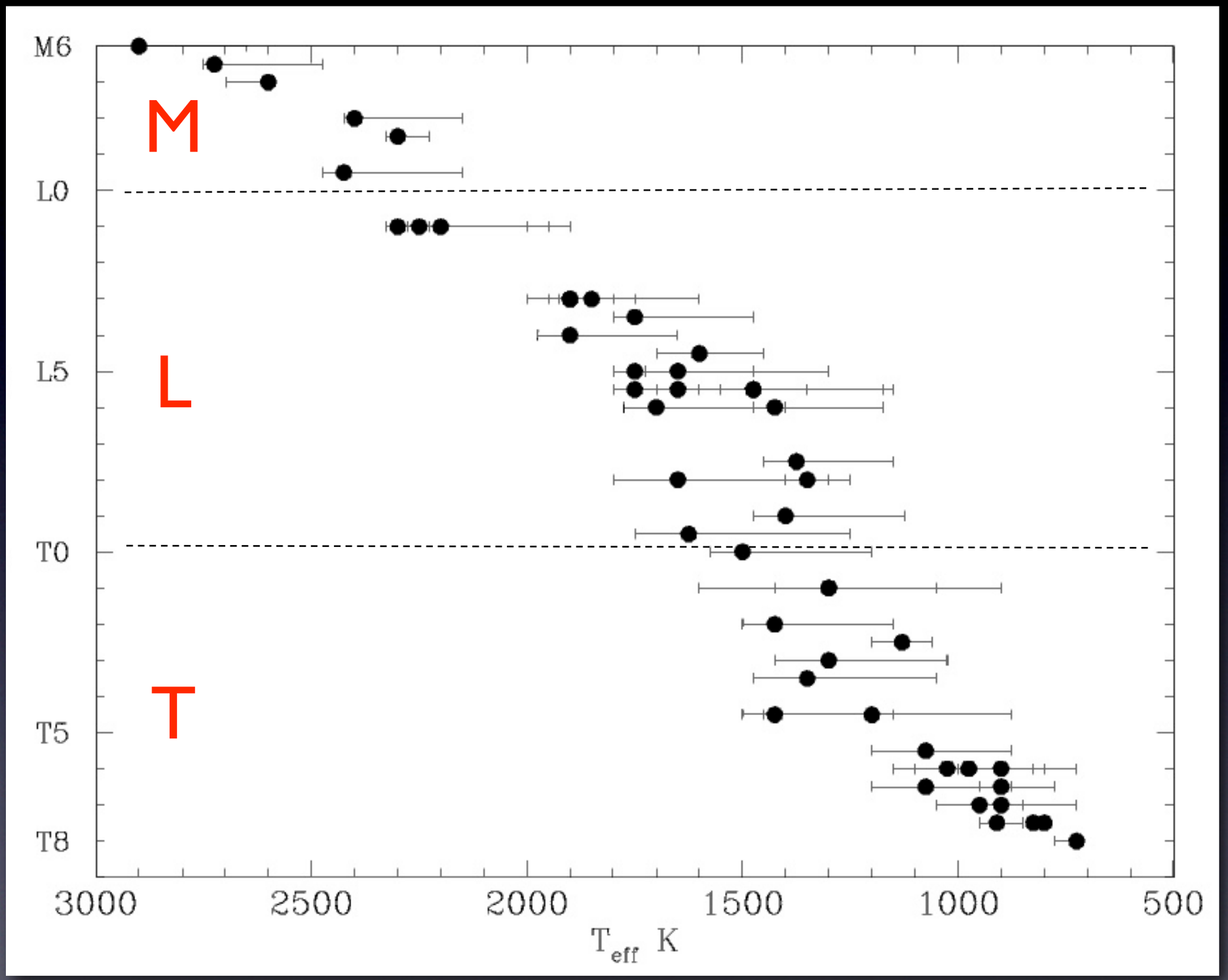
J brightening is real





Liu et al. (2007)

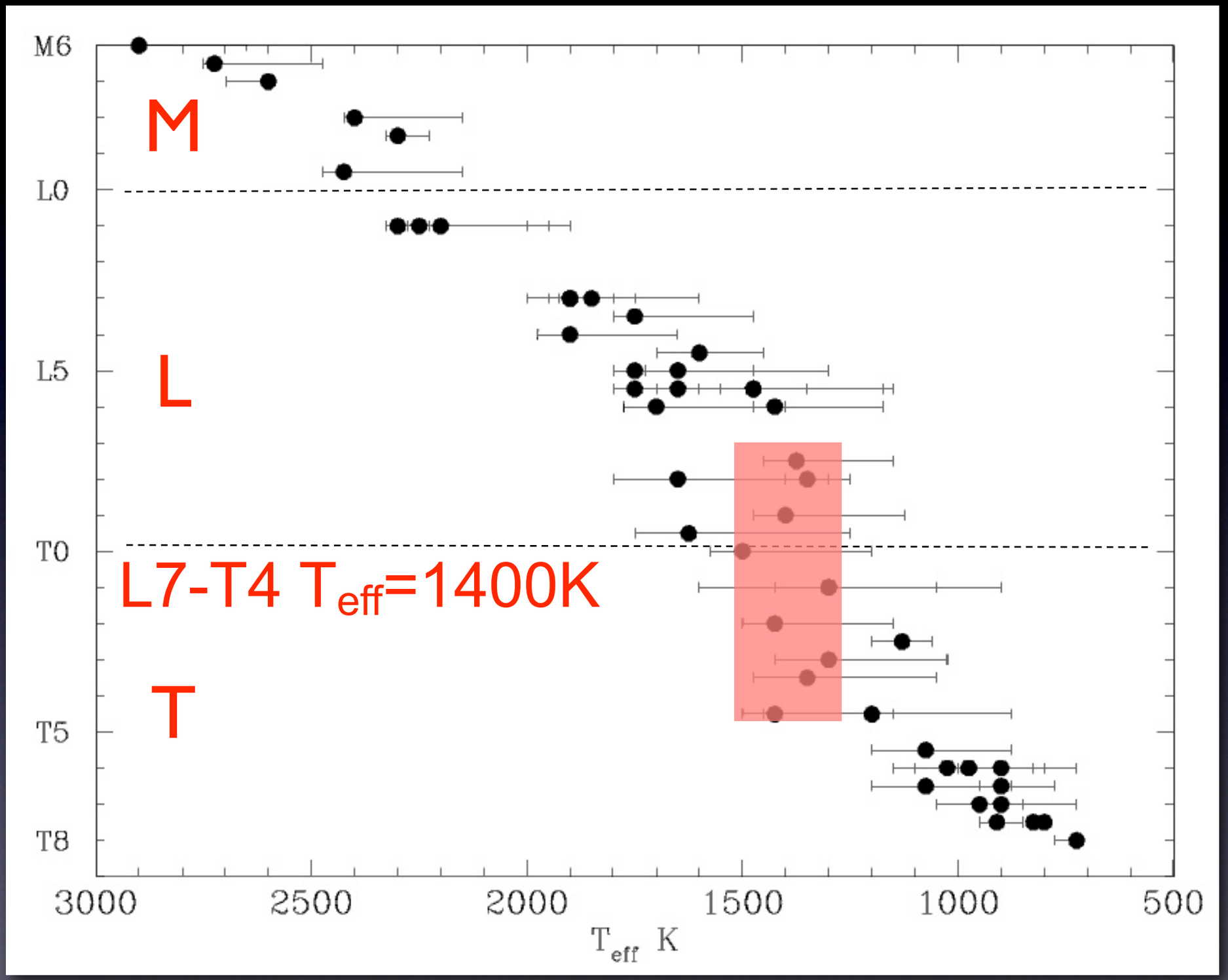
Transition is at ~constant T_{eff}



T_{eff} and (infrared) spectral type adjusted for recently confirmed binaries and newer objects Error bars reflect unknown ages. The coldest object in the plot is the T8 2MASS J0415-09.

data from Golimowski et al. (2004) & Luhman et al. (2007)

Transition is at ~constant T_{eff}



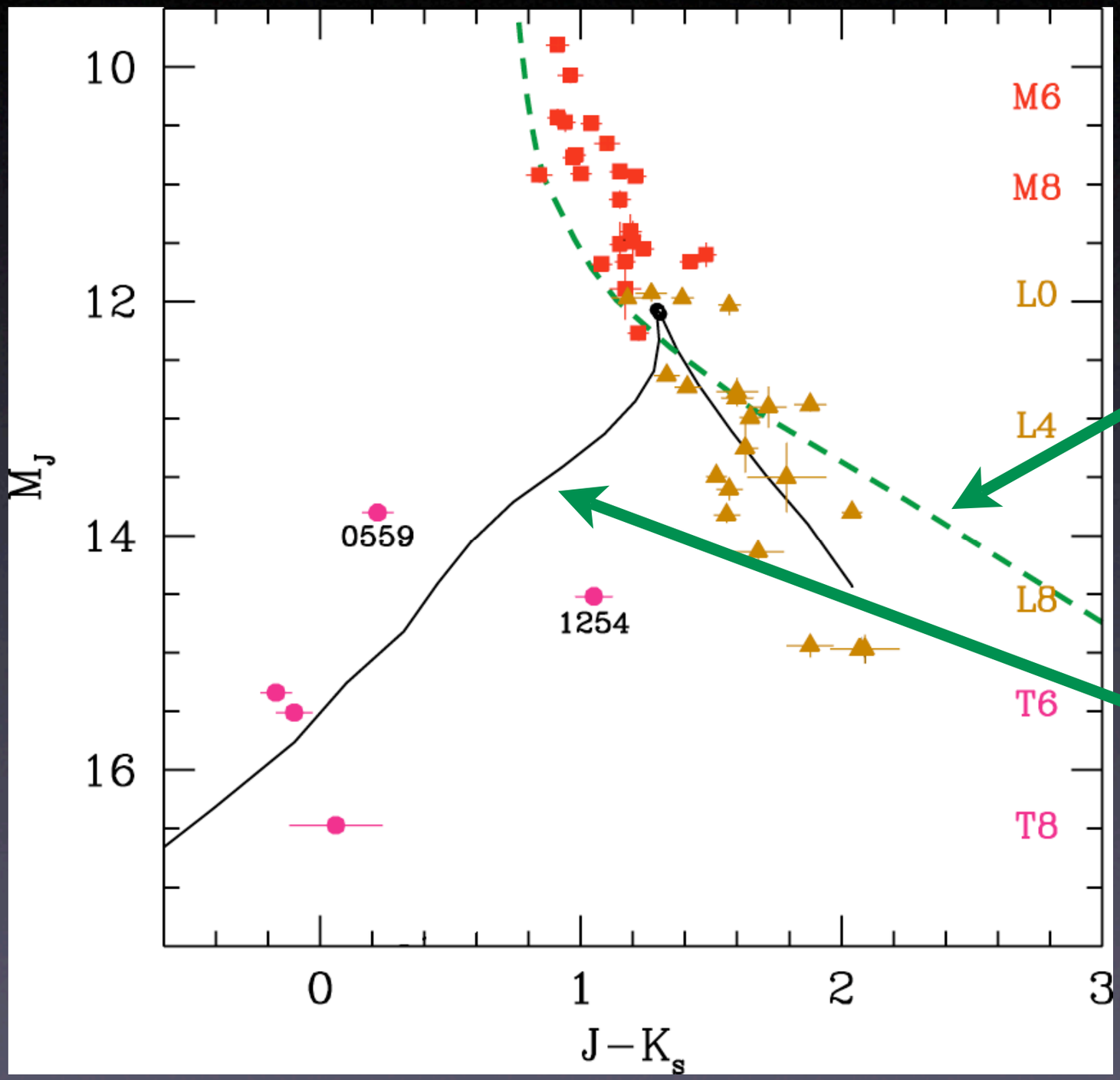
T_{eff} and (infrared) spectral type adjusted for recently confirmed binaries and newer objects Error bars reflect unknown ages. The coldest object in the plot is the T8 2MASS J0415-09.

data from Golimowski et al. (2004) & Luhman et al. (2007)

Key Questions

- What causes apparently rapid removal of clouds along with color change and brightening?
- How to constrain T_{eff} and g from spectra of L and T dwarfs as complicated by clouds?
- What other dynamical processes are important?
- Bridging the gap to the planets

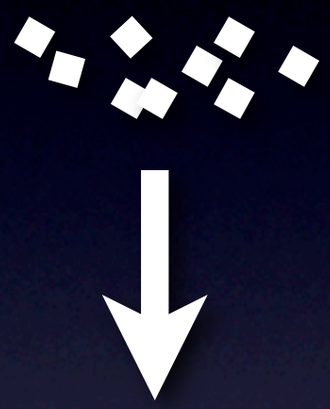
Need for Cloud Model



- No precipitation yields colors that are too red
- Perfect precipitation yields colors too blue

Cloud Modeling Schools

Top - Down



Helling et al.

Bottom - Up

Ackerman & Marley

Fixed

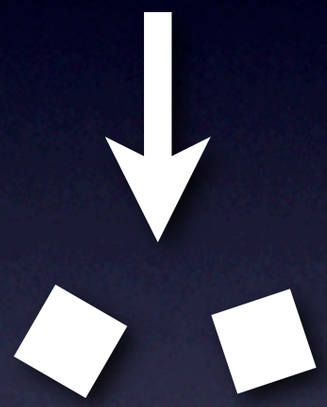
Tsuji, Arizona

Chemical Equilibrium

PHOENIX - DUSTY

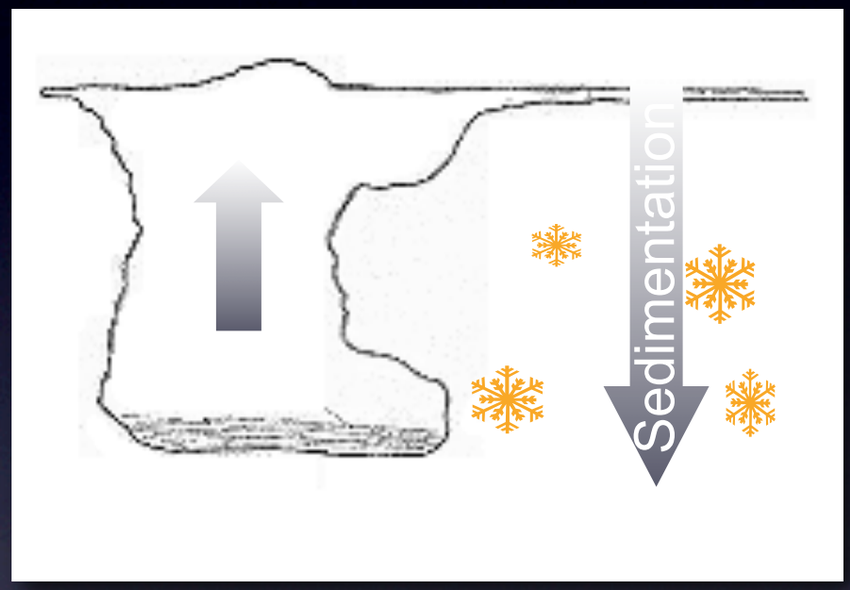
Cloud Modeling Schools

Top - Down



Helling et al.

Bottom - Up



Ackerman & Marley

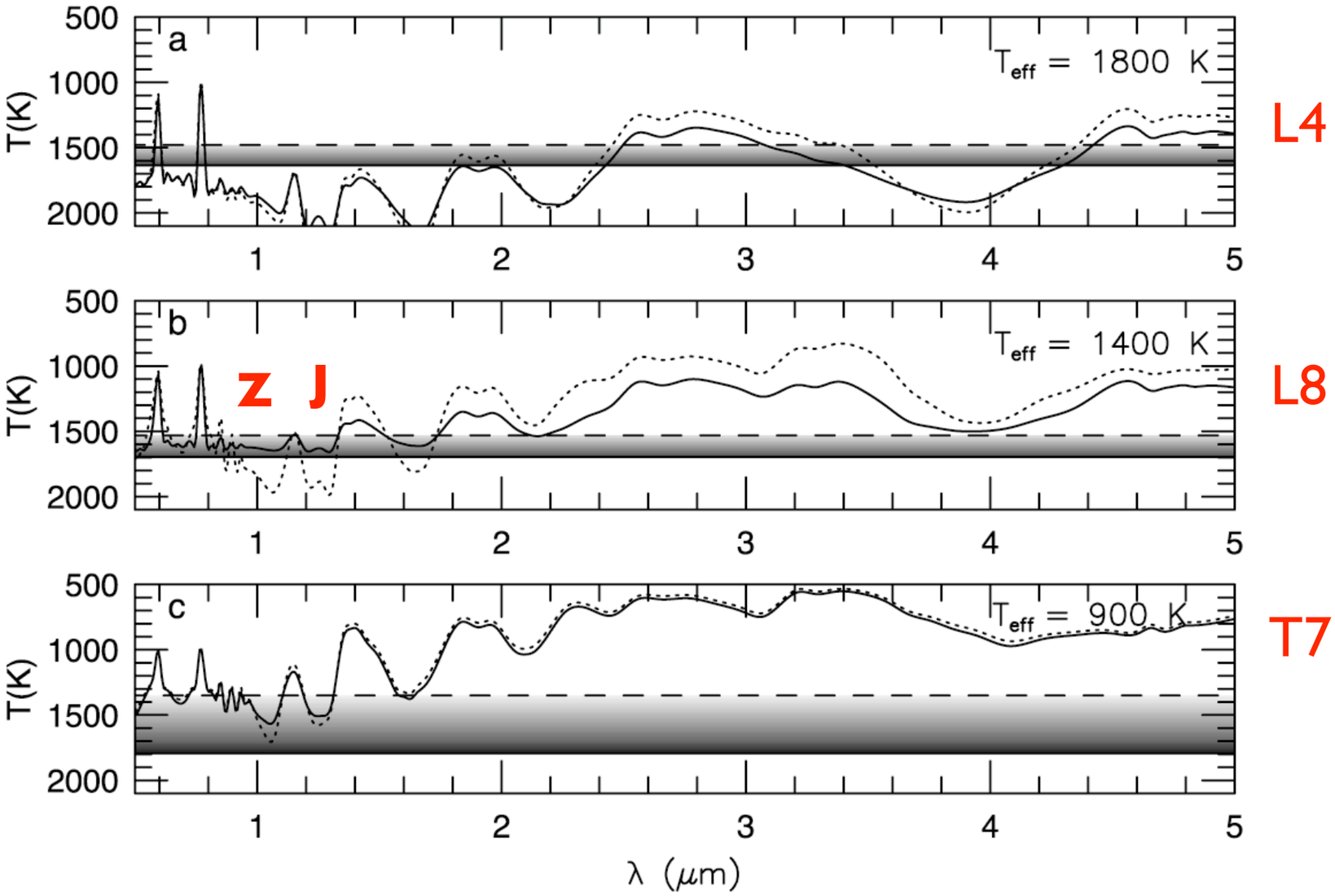
Fixed

Tsuji, Arizona

Chemical Equilibrium

PHOENIX - DUSTY

With the Rain...



L4

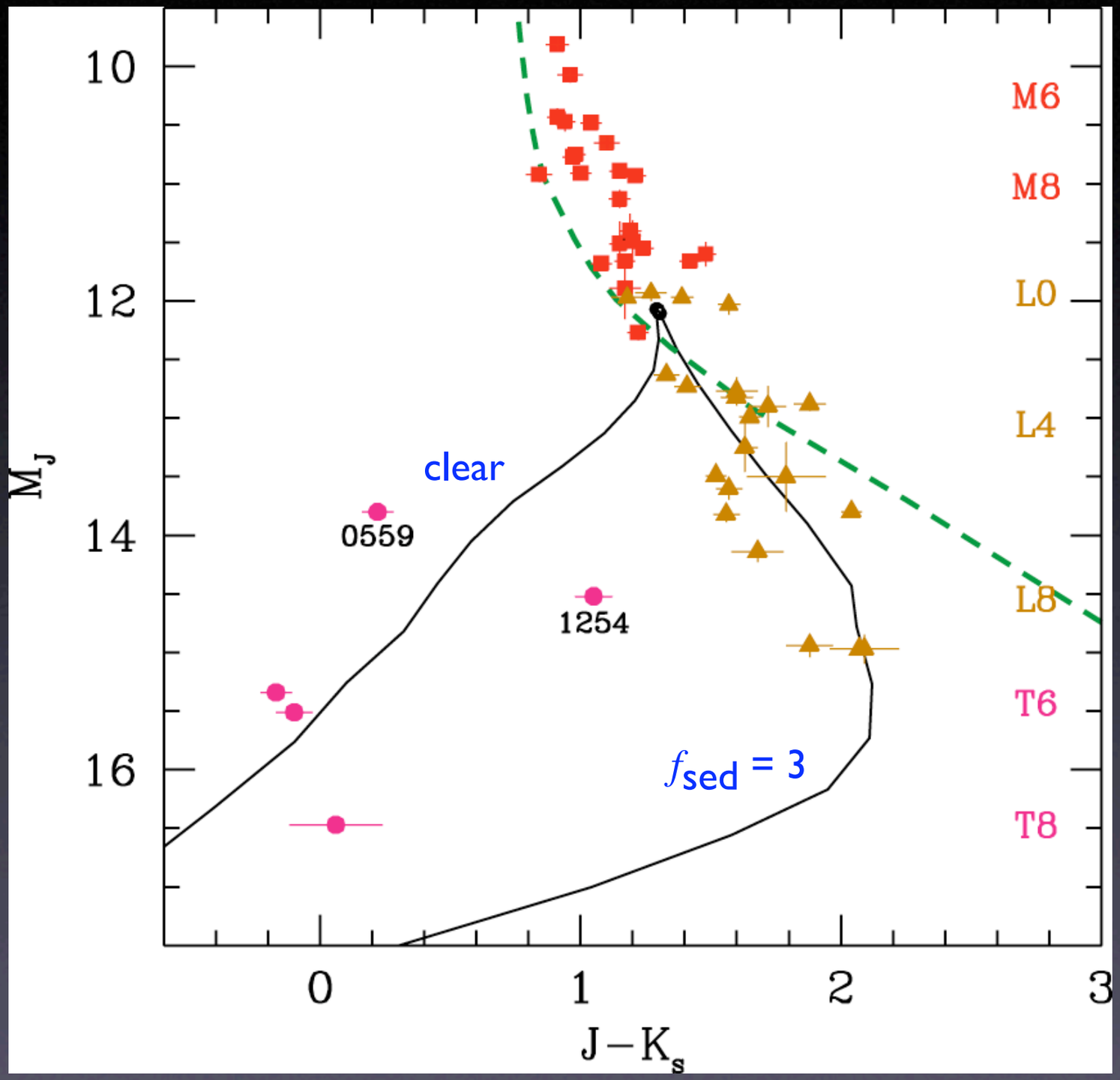
L8

T7

- Early L's cloud is optically thin
- Late L's cloud is optically thick, strongly affecting Z and J bands
- T dwarfs cloud is below photosphere
- In cool overlying air CO → CH_4, hastening turn to blue in J-K

Ackerman & Marley (2001)

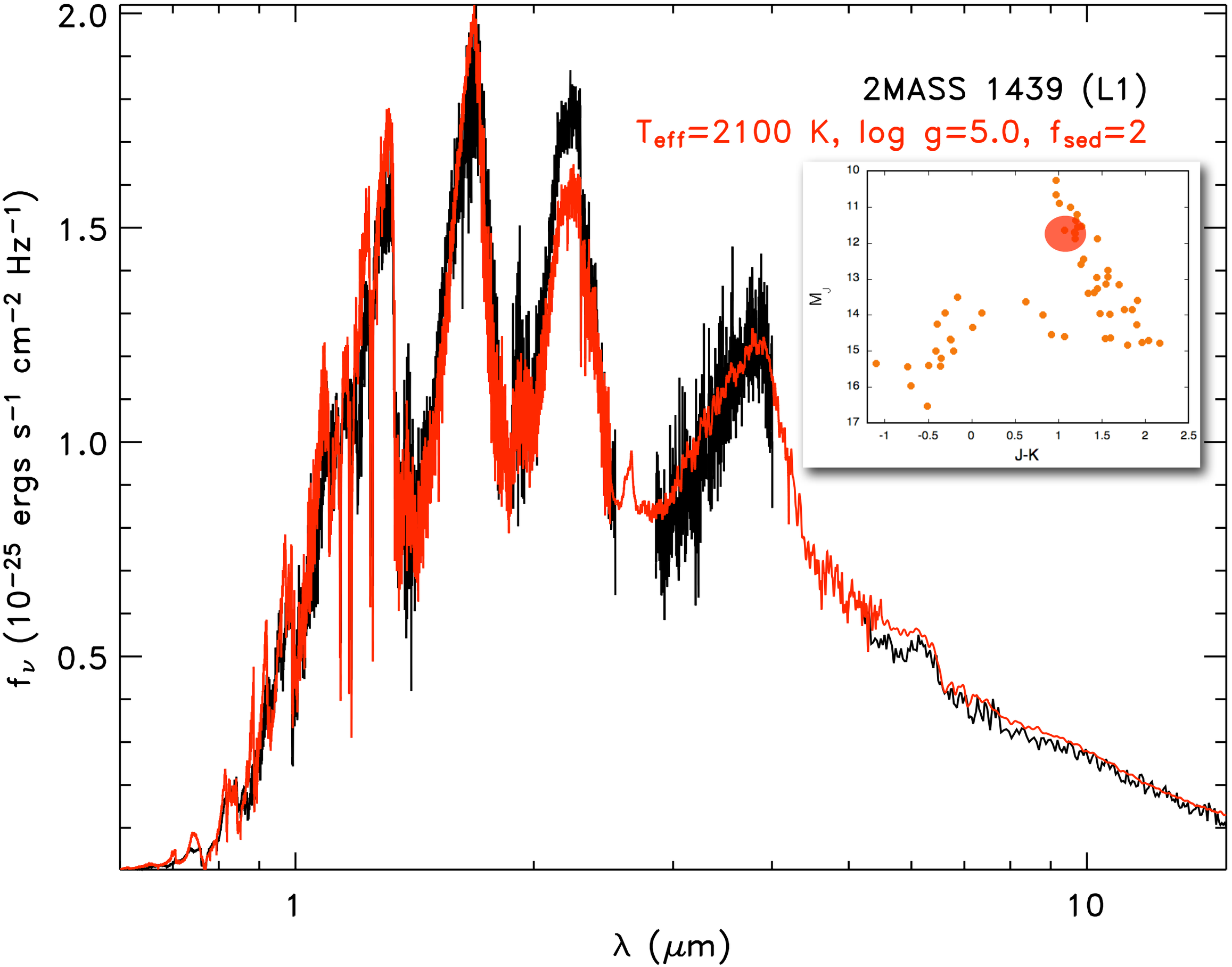
...Comes the Blues

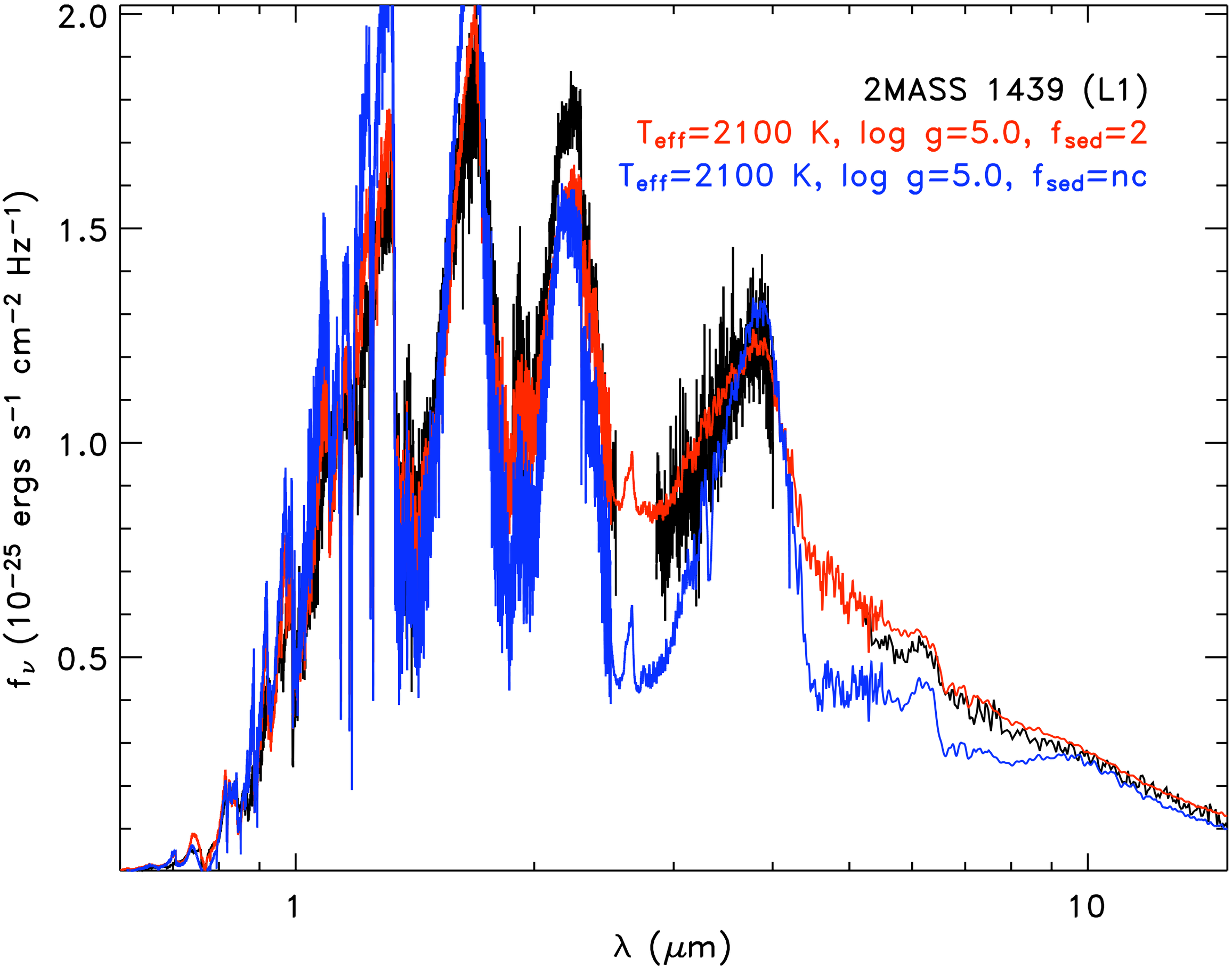


Burgasser et al. (2002)

Results for self-consistent coupling of cloud & r/t model with f_{sed} = 3:

- fits L dwarfs better than well-mixed cloud
- J-K ≤ 2 for L dwarfs
- turns to blue as cloud sinks out of sight


2MASS 1439 (L1)
T_{eff}=2100 K, log g=5.0, f_{sed}=2
f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})
2.0
1.5
1.0
0.5
1
10
λ (μm)
M_J
10
11
12
13
14
15
16
17
-1
-0.5
0
0.5
1
1.5
2
2.5
J-K


2MASS 1439 (L1)
T_{eff}=2100 K, log g=5.0, f_{sed}=2
T_{eff}=2100 K, log g=5.0, f_{sed}=nc
f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})
2.0
1.5
1.0
0.5
1
10
λ (μm)

2MASS 1507 (L5)

T_{eff}=1700 K, log g=4.5, f_{sed}=2

T_{eff}=1700 K, log g=4.5, f_{sed}=nc

f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})

λ (μm)

M_J

J-K

DENIS0255 (L8)

T_{eff}=1400 K, log g=4.5, f_{sed}=2

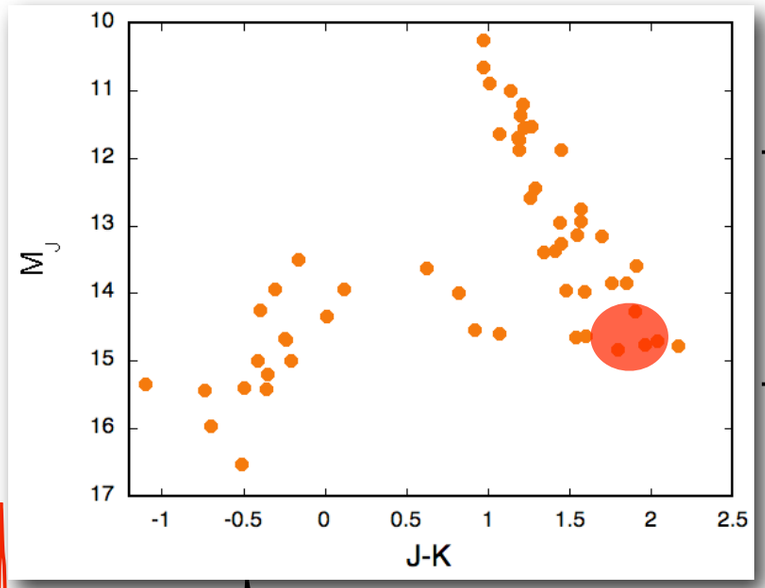
T_{eff}=1400 K, log g=4.5, f_{sed}=nc

f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})

3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

1
10

λ (μm)



DENIS0255 (L8)

T_{eff}=1400 K, log g=4.5, f_{sed}=2

T_{eff}=1400 K, log g=4.5, f_{sed}=nc

f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})

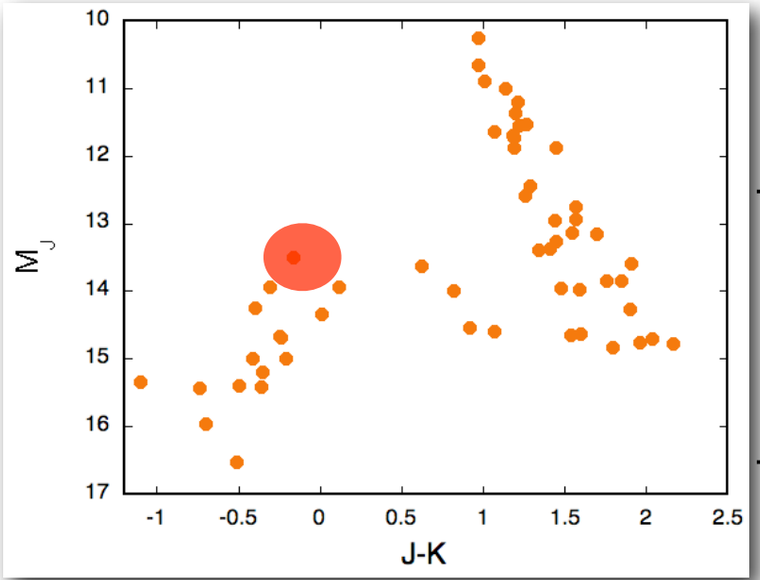
λ (μm)

M_J

J-K

2MASS 0559 (T4.5)

T_{eff}=1300 K, log g=4.5, f_{sed}=nc



f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})

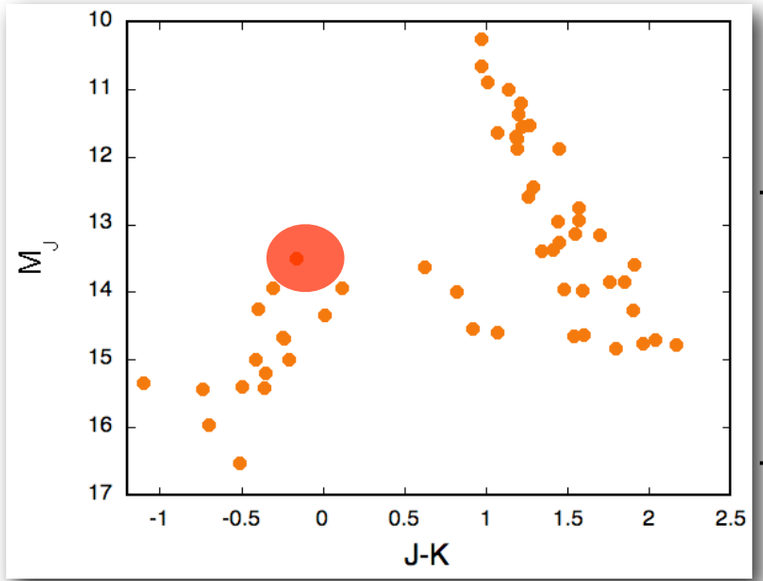
1.2
1.0
0.8
0.6
0.4
0.2
0.0

1
10

λ (μm)

2MASS 0559 (T4.5)

T_{eff}=1300 K, log g=4.5, f_{sed}=nc

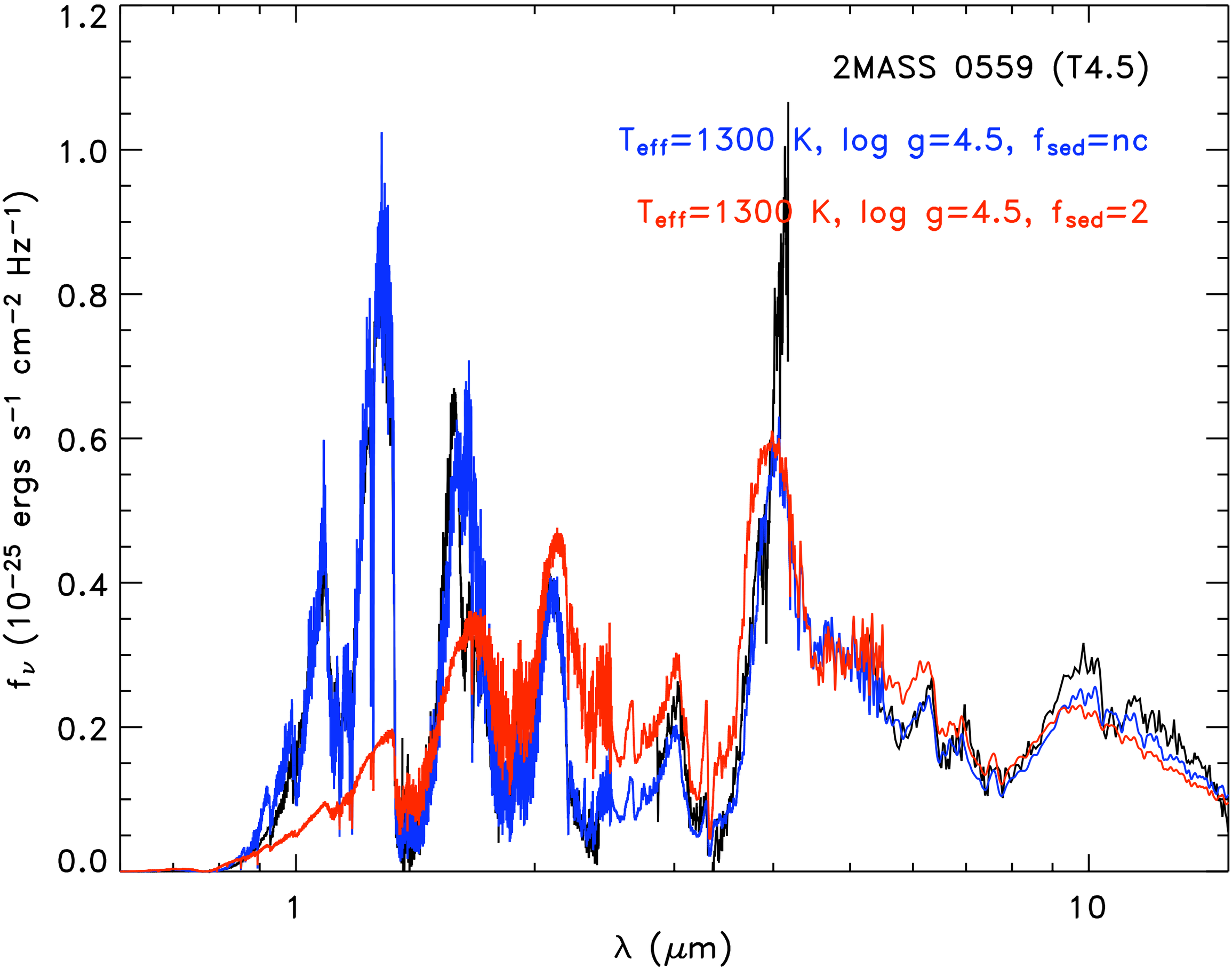


f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})

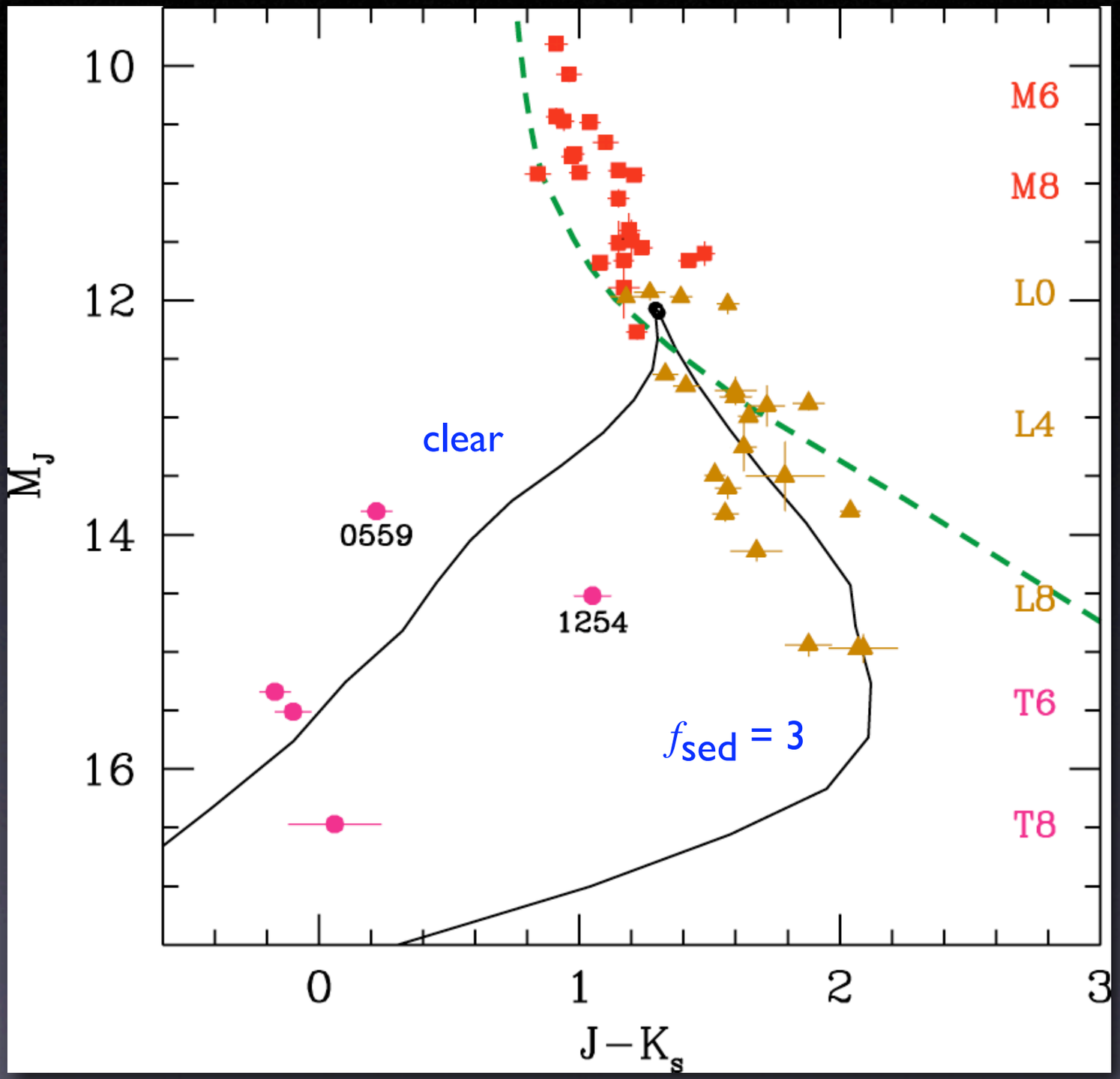
1.2
1.0
0.8
0.6
0.4
0.2
0.0

1
10

λ (μm)

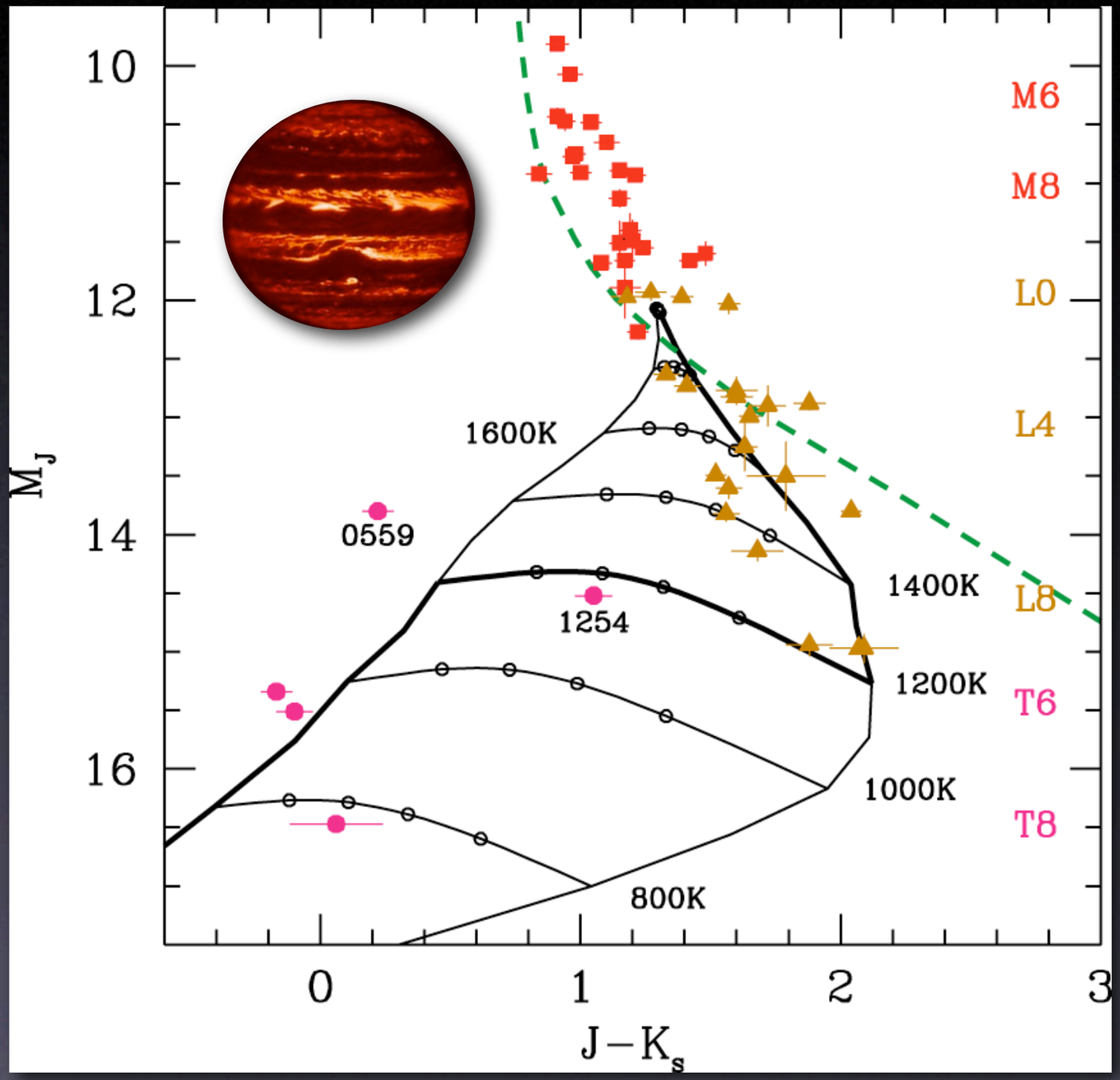

2MASS 0559 (T4.5)
T_eff=1300 K, log g=4.5, f_sed=nc
T_eff=1300 K, log g=4.5, f_sed=2
f_ν (10^-25 ergs s^-1 cm^-2 Hz^-1)
λ (μm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1
10

Sinking Cloud Fades too Slowly



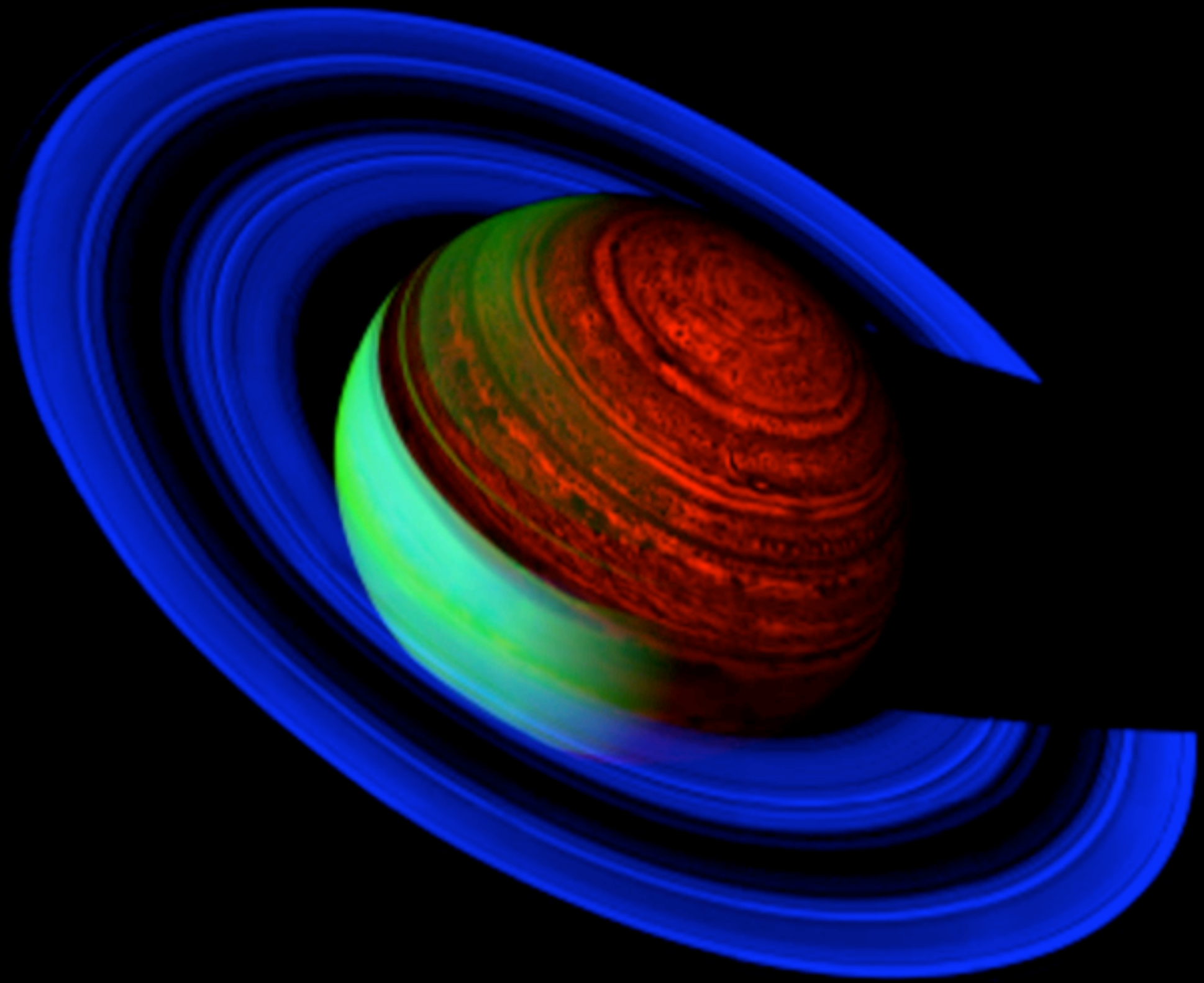
Burgasser et al. 2003

Hot Spot Hypothesis

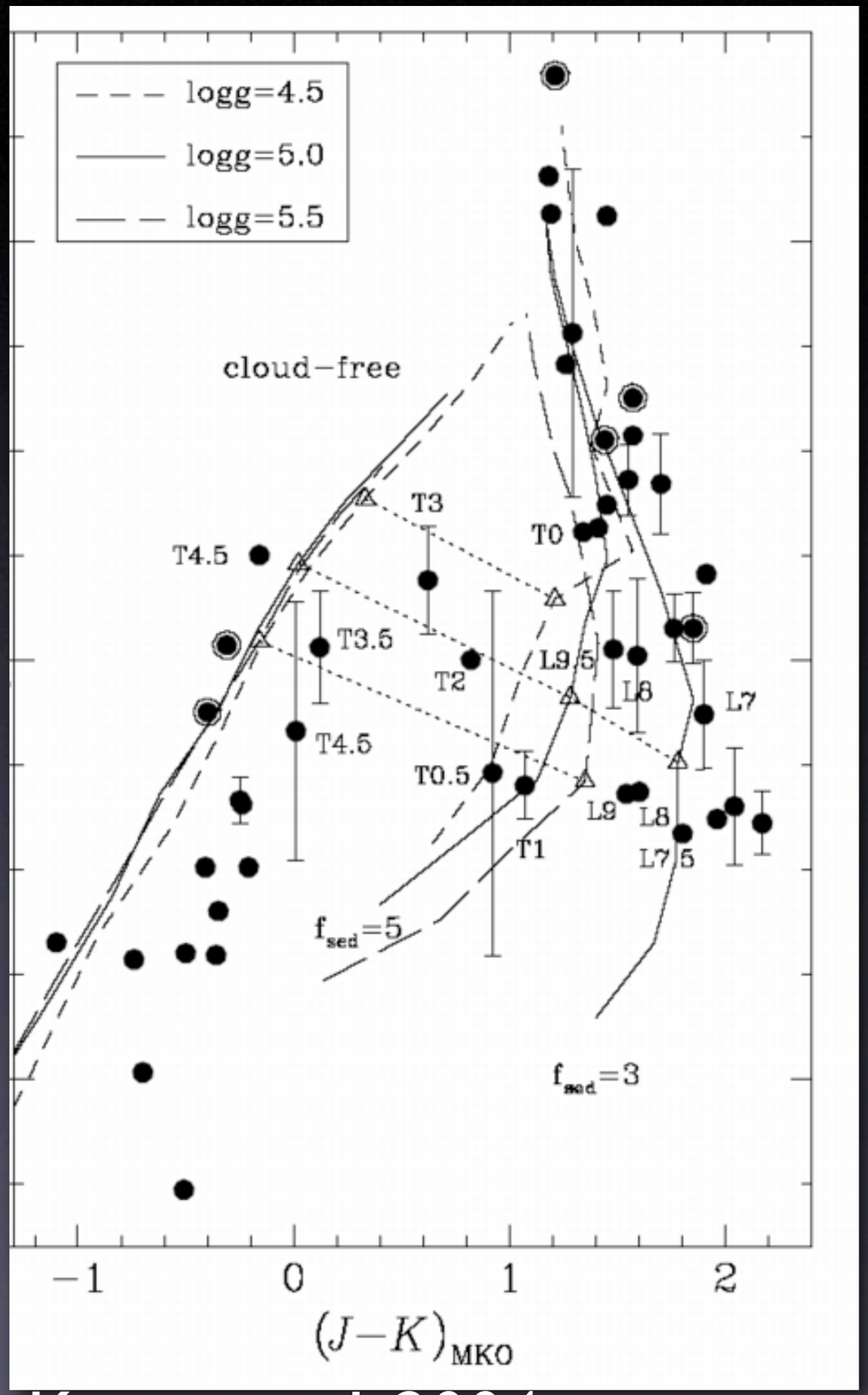


- cloud holes appear at T_{eff} ~ 1350 K
- explains brightening & sudden blueward shift
- small T_{eff} range in early T's
- but why?

Burgasser et al. (2002)



Alternatively...

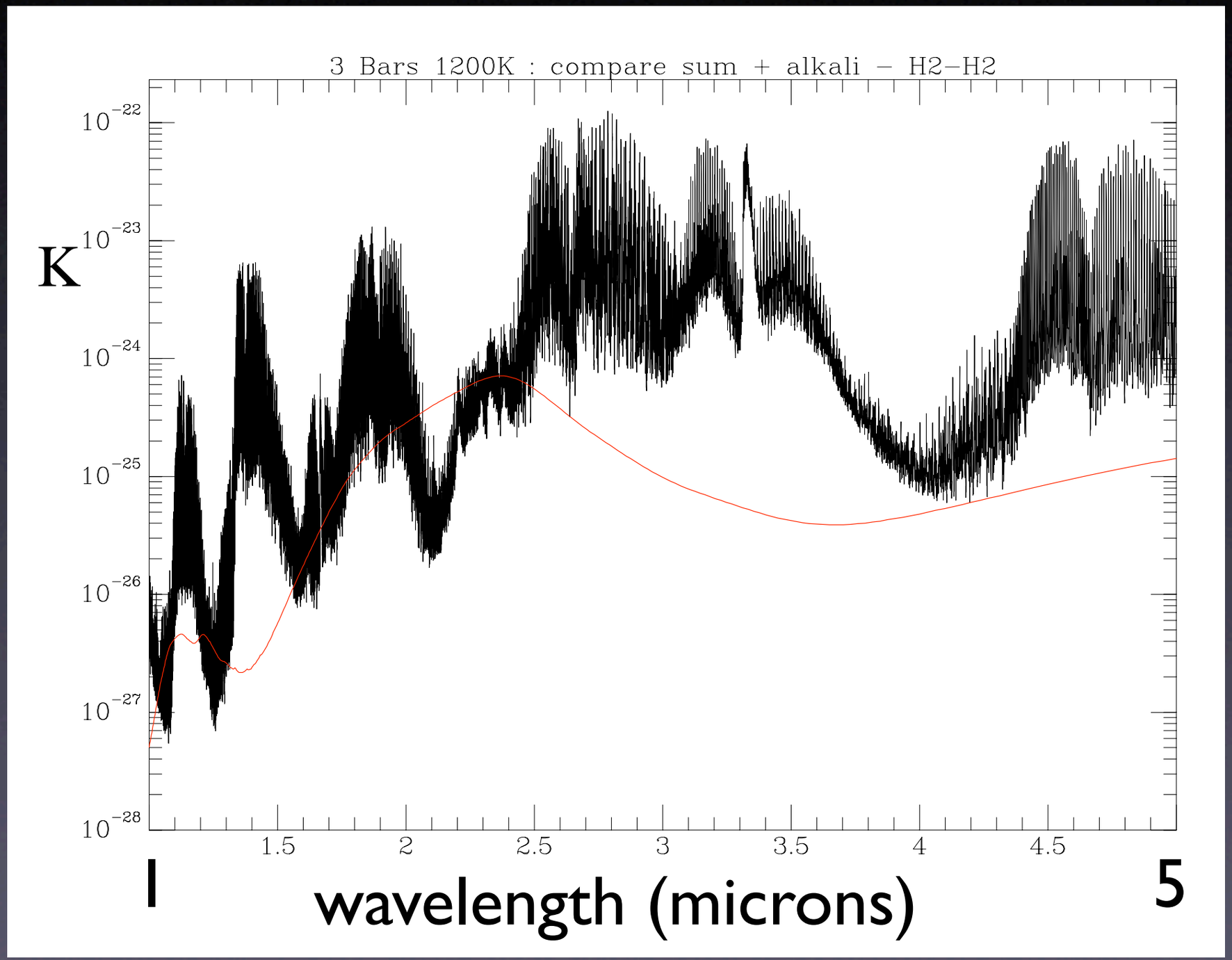


Knapp et al. 2004

M_J

- Change in atmospheric dynamics leads to rapid, global increase in sedimentation efficiency, not patchiness (Hilo rain)
- Cloud collapses
- Consistent with mid-T spectral fits
- But...
  - FeH
  - variability

Spectral Fitting Alone is not Adequate



- Too many free parameters (cloud, metallicity, T_{eff}, g, K_{zz})
- Models have missing or incomplete opacity sources (FeH, CH_4, H_2-H_2)
- Need....

Fiducial Objects

Need Model Independent

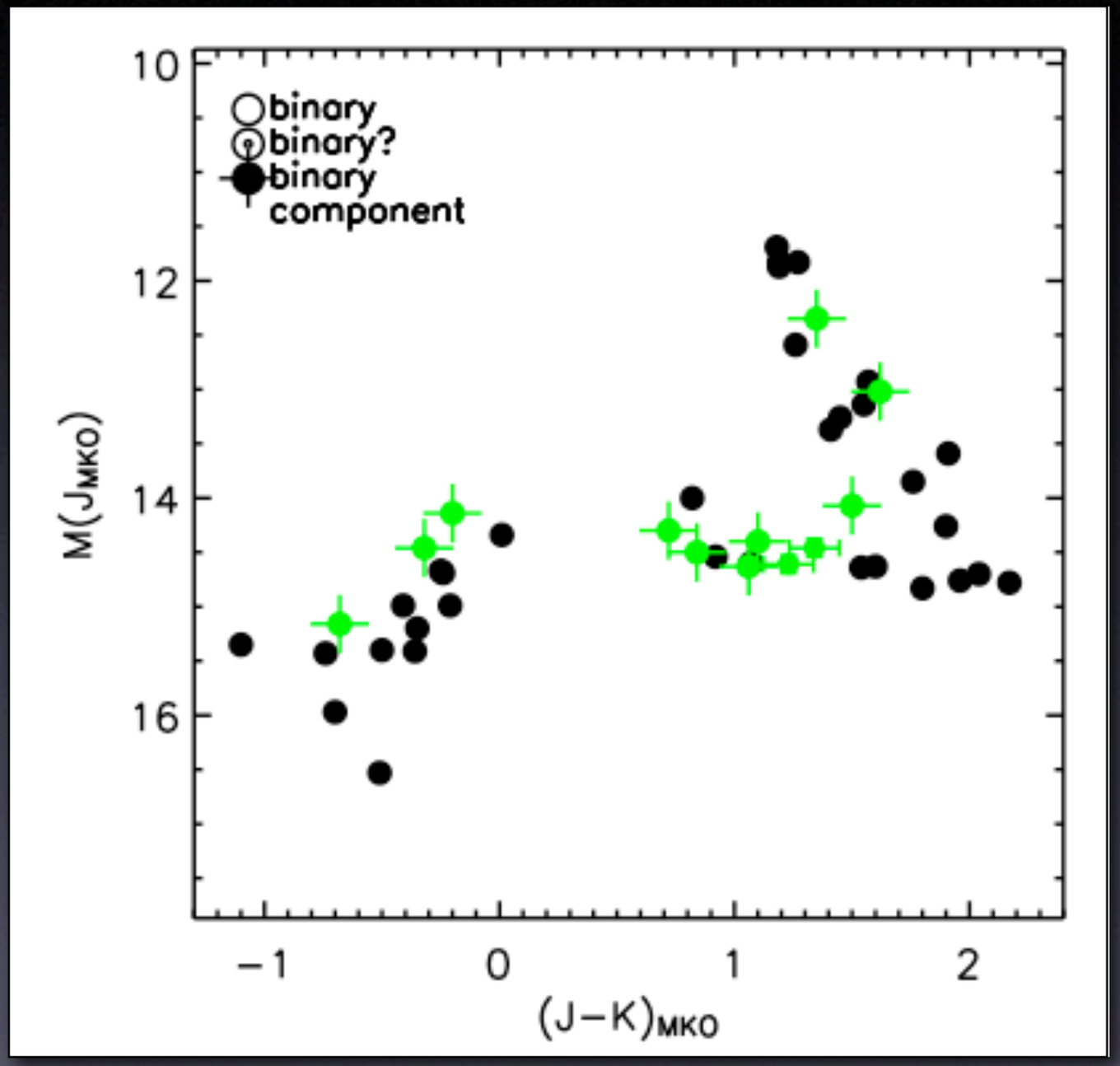
T_{eff}

Mass

g

Fe/H

Fiducial Objects



Liu et al. (2007)

Need Model Independent

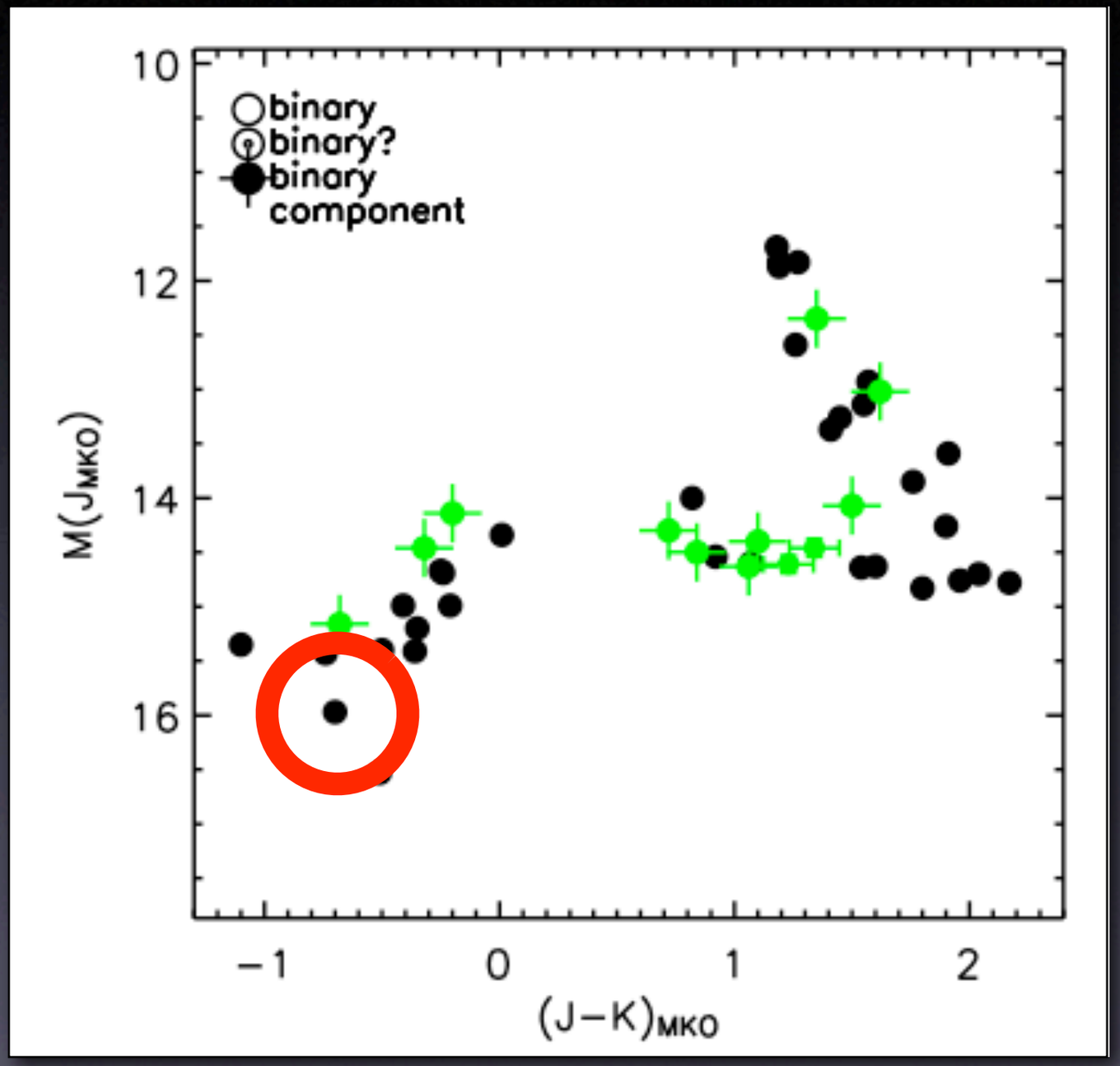
T_{eff}

Mass

g

Fe/H

Fiducial Objects



Liu et al. (2007)

Need Model Independent

T_{eff}

Mass

g

Fe/H

Lesson for Exoplanets

- Clouds are exceptionally important
- Clouds are challenging
- Fundamental interpretation hinges on unproven cloud models

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Summary

- Exoplanets
  - Evidence for hot stratospheres
  - Interplay of radiative cooling and dynamics is important
  - Two classes of planets
- Brown Dwarfs
  - L to T transition hinges on clouds, which are challenging to model
  - Need to find fiducial objects to validate models
- Solar system expertise helps!

Help Wanted

Wildy succesful startup field has immediate and ongoing opportunities for planetary scientists with expertise in

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- atmospheric dynamics
- chemistry
- seasonal change
- radiative transfer
- cloud physics
- photochemistry
- spectroscopy
- photometry
- origins
- atmospheric modeling
- interior structure
- ...

Sorry, stock options not available.